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A DRY ROT OF THE IRISH POTATO TUBER.

By E. Mead Wilcox, George K. K. Link, and Venus W. Pool.

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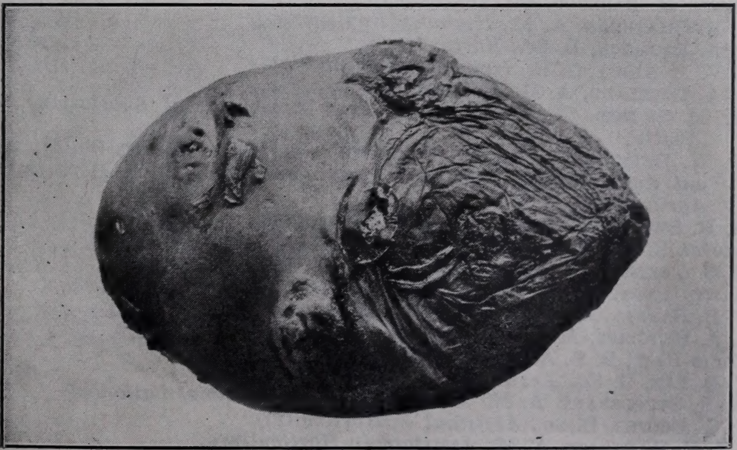

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* Resigned, to take effect February 1, 1913.

AMERICAN MUSEUM OF NATURAL HISTORY

TABLE OF CONTENTS.

PAGE
Introduction 5
History and distribution 6
Economic importance 9
Symptoms 11
Morphology of the causal organism 11
    Occurrence of the organism 15
    Technique 16
    Macroscopic characters 18
    The mycelium 19
    Spore septation 20
    Influence of temperature 39
    Humidity 42
    Color 42
    Conidiophores 45
    Chlamydospores 45
    Spore measurement 45
    Summary 47
    Fusarium tuberivorum sp. n. Wilcox and Link 48

Etiology—

    Tuber infections 49
    Contact inoculation 50
    Eye punctures of Early Ohio 50
    Surface punctures of Early Ohio 50
    Surface inoculations of Early Ohio tubers after removal of the skin 51
    Smear inoculations on eye, lenticel, or surface of Early Ohio 52
    Inoculation of "new" tubers of Early Ohio 58
    Natural field inoculations 59
    Natural infection with dry rot 64
    Artificial infection 65
    Comparative studies of *Fusarium oxysporum* and *Fusarium tuberivorum* 68
    Morphogenic and chromogenic influence of acidity of the medium upon *Fusarium oxysporum* and *Fusarium tuberivorum* 68
    Chromogenic influence of light upon *Fusarium oxysporum* and *Fusarium tuberivorum* 77
Resistance and susceptibility 79
    Other inoculations 80
Methods of control 82
Summary and conclusions 84
Bibliography 85

28 plates.
15 text figures.
7 graphs.
1 map.

A DRY ROT OF THE IRISH POTATO TUBER.

BY E. MEAD WILCOX, GEORGE K. K. LINK, AND VENUS W. POOL.*

INTRODUCTION.

The first specimens of the dry rot herein described were received by the department of Agricultural Botany during the winter of 1907-1908 from western Nebraska. A preliminary survey of the situation showed clearly the importance of this new rot, and an exhaustive investigation of the disease was outlined and has been continued to the present time. During the summers of 1909 and 1910 a branch laboratory was maintained at Alliance in quarters generously provided by the local authorities to whom we are under obligations for the facilities placed at our disposal. In this manner we were able to study the prevailing local conditions and to secure results quite impossible of attainment in a laboratory located at a great distance from the seat of the trouble.

In addition to the authors of the present publication the following persons have at various times been connected with this investigation: Roland Elisha Stone, George Herbert Coons, and Ethel Field. To these persons we here extend our thanks for their faithful and conscientious service. Much of this work would have been impossible without the generous support of the Legislature in providing special funds for the work of the department of Agricultural Botany, while the more technical investigations have been made possible thru the use of the Adams Fund. We wish further to express our thanks to a large number of potato growers in the Sand Hill and High Plains regions for their interest and assistance, while to E. W. Hunt we are indebted for the earlier specimens furnished and for much information as to the field conditions secured thru the use of a conveyance provided thru the public spirit manifested by W. L. Newberry of Alliance. We are indebted to the Department of Geography for the map of Nebraska soil regions.

The present publication gives the results secured to date in our investigation of this disease. Certain other problems remain unsolved and these are now receiving attention. Among these may here be mentioned the determination of the real nature of the apparent resistance of young tubers and the stems to the invasion of this fungus.

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* Resigned November 1, 1911. Responsibility for all statements in this bulletin rests with the first two authors.

HISTORY AND DISTRIBUTION.

It seems probable that some form of tuber dry rot due to species of *Fusarium* occurred long before it attracted the attention of potato growers or was investigated by plant pathologists. We have included in the bibliography references to some of the earlier accounts of what appears to be the same type of dry rot, tho in most cases the data given are not sufficient to enable one to express a positive opinion as to the identity of the causal organism.

One of the earliest published accounts of a tuber dry rot was by Clinton 1895. He described (p. 139) a "bundle blackening" in the following words: "This is a fungous trouble of stored potatoes which shows as small dots or lines a short distance from the surface. The fungus gains entrance probably after the potatoes are gathered through the dead stem, and proceeds from this through the bundles, causing them to turn black as the result of its attack. The fungus is quite similiar to the one causing the following trouble." He then described (p. 139) the disease which he called "Dry End Rot" as follows: "It affects all the tissues as it slowly advances forward, until, perhaps, the whole tuber is destroyed. As in the preceding case, the trouble begins at the stem end, the fungus gaining entrance after the rupture of the tuber from the plant." He believed that this latter disease was caused by *Fusarium solani* and recommended that only sound tubers be placed in storage and these kept (p. 140) "in a dry, cool place."

Price 1897 described (p. 926) from Texas the "Dry Rot (*Fusarium solani*)" as follows: "This disease appears on the tubers in the form of a dark brown spot which is sunken beneath the surface of the potato. The disease spreads more rapidly if the tubers be kept moist."

Bessey 1899 may possibly have had this same disease in hand and if so this would be the first reference to the disease in Nebraska.

Rolfs 1901 referred (p. 26) to the "Irish Potato Summer Rot" and says: "There is a rot of the Irish potato that seems quite distinct from *Bacillus solanacearum*, but the exact cause does not seem to have been ascertained. There is a fungus resembling a *Fusarium* quite constantly present but it may not be the cause."

Smith and Swingle 1904 described a dry rot and wilt of potatoes which they claimed was due to *Fusarium oxysporum*. Subsequent authors in their discussion of similar symptoms of potato diseases have largely been guided by and often have merely repeated, without verification, the conclusions of Smith and Swingle.

What appears to be the same disease is described by anon. 1906 from England under the name "Winter Rot" and is claimed to be due to *Nectria solani*—an organism often mentioned in the literature as the "perfect" stage of *Fusarium solani.* This author says (pp. 739-740): "It attacks stored potatoes, and is always present to some extent, but as a rule only reaches the proportions of an epidemic during hot, dry seasons. The tubers only are attacked, and inoculation, through spores present in the soil, takes place when the tubers are young; but, as a rule, there is no obvious disease present when the tubers are lifted, although the mycelium of the fungus is present in the tissues. During the following season the most perfect stage of the fungus, in the form of minute crimson-red points, develops on the skin of the diseased tubers."

Norton 1906 referred (p. 67) to a "dry-rot" as caused by *Fusarium oxysporum* in the following words: "The disease is indicated by the lighter colored and more or less rolled up leaves. When dug the potatoes may appear sound, but internally show black or brown streaks, and later are destroyed at least at one end by the dry rot."

Morse 1908 says (p. 2): "Another disease of the stem and tuber which is usually designated as the *Fusarium* dry rot caused by the fungus *Fusarium oxysporum* Schlecht. has been found for the first time in Maine during the past summer. It is well known that this disease, and it is probable that black-leg as well, is disseminated by means of seed tubers from infected fields."

Pethybridge and Bowers 1908 have described a dry rot of the potato tuber from Ireland where they say it first appeared in 1902 on the "Snowdrop" potato. They say (p. 548): "They were fairly firm to the touch, but more or less shrivelled, with the skin contracted into wavy wrinkles. At various points on the tubers the skins were broken through by fungus pustules. These were whitish on the surface; but on gently rubbing them the base of the pustule was seen to be of a blue color. On standing for some time, especially in the light, the surface of the pustules changed from whitish to a salmon-pink; on the less well-illuminated undersides of the tubers and on those in the dark the pustules remained for a long time whitish blue."

They ascribed this rotting to the fungus *Fusarium solani* Saccardo and emphasized the relationship of the rotting to pre vious wounding of the tubers. From 80 to 86 per cent of rotted tubers were found to have been previously wounded to some extent.

Duggar 1909 in his discussion of the "Dry Rot of Potatoes" (p. 317) says: "It is very probable that many of the diseases described under the name of dry rot, end rot, bundle blighting,* etc., are due to the fungus here discussed. Smith and Swingle have, by careful cultural and inoculation experiments, demonstrated the causal connection of a *Fusarium* with these types of disease, and they have taken as the name of the species here discussed the earliest described species of *Fusarium* associated with such diseases, namely the one given above, and they would regard as probably synonymous with this species half a dozen or more names subsequently applied to fungi described as producing more or less similar types of disease in the potato."

Lounsbury 1909 has described and illustrated a dry rot of the potato tuber found in Cape Colony as caused by *Nectria solani.* He says (p. 42): "The infection is introduced into the soil with diseased tubers and it remains there from season to season, so that a crop from perfectly healthy seed may get infected if grown on land that previously bore an affected crop. The disease generally enters at the stem end. The fungus develops most rapidly in the "vascular ring." From his reference to the "wilting" symptoms shown by affected vines and the last one of his figures it appears likely that he has confused the tuber dry rot and the *Fusarium* wilt referred to by various American plant pathologists.

Jack 1910 has described a gall of the potato tuber from Rhodesia due to a species of *Heterodera* with which is frequently associated a form of dry rot. He says (p. 1533): "Their presence in numbers is followed by decay in the tissues and frequently by the wilting of the infested plant. In the case of potatoes the infested tubers yield very readily to the attack of the common dry rot (*Fusarium solani*)."

Morse 1910 describing "Fusarium Dry Rot" (pp. 6-7) says: "The first symptoms are nearly always at the stem end, in the form of a brownish or blackened ring a short distance below the surface. At this stage the tuber may appear perfectly sound and healthy externally. Later there is a general discoloration of the flesh and a decided shrinkage of the tuber. The skin becomes wrinkled around the stem end, and the tuber becomes very light and often nearly as hard as wood. Infected potatoes may appear perfectly sound when placed in storage, and come out as described above."

"When this disease is suspected the stem end of the tuber should be cut off and examined for a darkened cinnamon-brown discoloration or ring in the tissues when cutting seed."

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* Probably refers to "bundle *blackening.*"

Tidswell 1910 described and illustrated a "Dry Rot" of the potato from New South Wales which he says is caused by *Fusarium solani,* an organism which he states should more properly be called *Fusarium oxysporum.* The illustration would indicate that he had to do with a dry rot quite similar to the one herein described tho by references to wilting of the tops of the plants, blackening of the vascular region, and root infection it seems certain that he had confused one or more other diseases with the dry rot of the tuber.

Manns 1911 has described from Ohio a disease called by him "the Fusarium blight and dry rot," which he says is caused by *Fusarium oxysporum.* Both his illustrations and the text show that the form of potato wilt described by Smith and Swingle 1904 and the present dry rot have been confused or rather united under one common designation. A full discussion of Manns' inoculation work will be found under Etiology.

Jones 1912 describes what he calls "Wilt and Dry Rot." His conception of the matter is clearly shown by the following statement (p. 4): "This is a fungus disease which attacks the roots causing the potato tops to wilt and die before full maturity. It may also invade the tubers at the stem end causing the flesh to blacken, and in bad cases leads to dry rot in winter storage, especially of the stem end of the tuber. It may be detected in the field by the wilting of the plants and in the tubers by cutting off a thin slice across the stem end, where the disease shows as a brownish black spot or ring where the vessels from the stem enter the flesh. This disease, as it occurs in the tuber, is likely to be confused with the other types of internal browning. The distinctive characters are that this disease causes the tops to wilt and die and that the internal blackening of the tuber increases during storage and may lead to dry rot."

ECONOMIC IMPORTANCE.

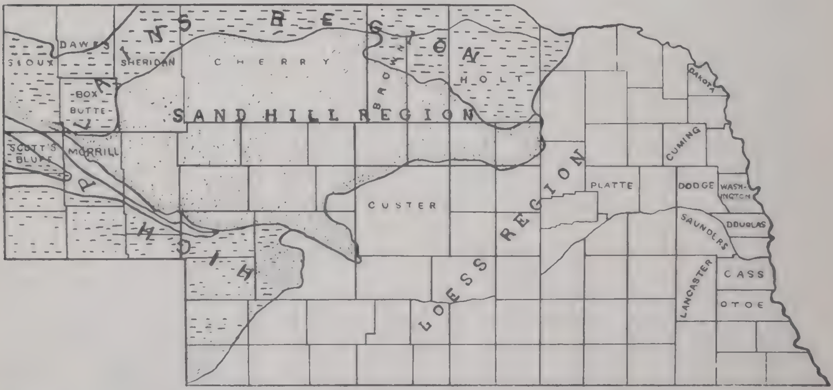
Potato growing has long been a prominent part of the agriculture of northwestern Nebraska. The early "homesteaders" introduced potato culture into this region on a small scale to supply local needs. With the coming of the railroads the industry made rapid strides and the Sand Hill and High Plains regions soon established an enviable reputation for the excellent quality of their potatoes.

The full significance of the potato crop in this region may be seen from the following statistics taken from the last United States Census Report covering the crop year 1909.

TABLE 1.—*Acreage and yield of potatoes during 1909 in counties producing 100,000 or more bushels.*

Counties	Acres	Bushels
Box Butte	7,020*	303,918*
Brown	2,197*	174,862*
Cass	1,305	112,103
Cherry	2,978*	150,105*
Cuming	1,280	125,608
Custer	2,410	159,308
Dakota	1,907	142,798
Dawes	2,322*	124,782*
Dodge	1,406	121,574
Douglas	2,509	231,177
Holt	1,791	130,371
Lancaster	2,267	170,561
Morrill	1,535	107,156
Otoe	1,512	137,484
Platte	1,442	127,674
Saunders	1,363	123,315
Scott's Bluff	6,452	774,815
Sheridan	8,590*	668,309*
Sioux	2,688*	191,051*
Washington	1,251	104,168
Totals	54,225	4,181,139
Totals for Nebraska	111,151	8,117,775

* These are the counties in the Sand Hill and High Plains regions where this dry rot is most prevalent.



Map showing the location of the Sand Hill and High Plains regions and indicating by name the counties each of which during 1909 produced 100,000 or more bushels of potatoes.

The losses from this dry rot have in some cases been very severe. The situation became so serious that during the spring of 1909 the Alliance Commercial Club sent the potato growers of that region a circular letter warning them against the danger of planting infected seed. This warning was based upon the fact that during the previous fall some of the largest potato buyers had refused to handle these potatoes on account of the serious losses during storage due to this dry rot. The department of Agricultural Botany thru circular letters addressed to many of the buyers and commission men handling potatoes found that during certain winters their losses from rotting of the tubers had been as high as 20 to 60 per cent.

One of the most serious losses due to dry rot is the fact that the disease forces the immediate sale of the potatoes as soon as dug. This tends to demoralize the market and places the grower at the mercy of the buyers since he is himself afraid to store his crop and wait for better prices. Taken all in all this dry rot is perhaps the most serious potato trouble our farmers have to contend with in the Sand Hill and High Plains regions.

SYMPTOMS.

The dry rot here described is a strict tuber rot affecting mature tubers only. Neither the stems nor the young tubers are ordinarily in the least affected. Natural infection is known to occur solely thru wounds produced in the process of digging or subsequent handling. In many cases this rot secures a foothold thru wounds made by scab-producing animals of certain sorts and perhaps even thru scab spots due to fungus parasitism, tho the latter method is certainly very rare if we may judge from the laboratory experiments. The fungus cannot invade the tuber either about the "eyes" or thru the normal lenticels.

The rotting is rather slow and in general within four to six weeks from one-third to three-fourths of the tuber is destroyed. The epidermis of the rotted portion becomes slightly wrinkled and usually has a characteristic bluish color. On account of the rapid destruction of the underlying tissues the surface over these areas soon becomes distinctly depressed (Plate I).

The rot may make its appearance at any point on the surface of the tuber tho more commonly perhaps at the bud end of the tuber. There is no watery degeneration of the tuber unless other organisms gain entrance, so that this is in fact a dry rot.

MORPHOLOGY OF THE CAUSAL ORGANISM.

Previous to 1910 no comprehensive work on the genus *Fusarium* had appeared which could be considered authoritative and the genus was in a very chaotic condition. A species was defined by a few lines of description in which the name of the host played an important part. In 1910 appeared a publication entitled "Grundlagen einer Monographie der Gattung Fusarium (Link)," by Appel and Wollenweber. In this the authors have laid the foundation for a systematic treatment of the genus upon morphological characters.

During the fall of 1911 the morphological study of this organism, previously shown to be responsible for the dry rot of the Irish potato tuber herein described, was undertaken along the lines laid down by Appel and Wollenweber.*

The genus *Fusarium* was defined by Link in 1809, together with the allied genera, *Fusidium, Fusisporium,* and *Atractium.* From time to time Link dropped one or the other or combined them in various ways. In one of his late works in 1824 he defines the genera *Fusisporium*, *Fusidium*, and *Fusarium,* using the presence or absence of a thallus as prime character. As it happened the genera were thereby also divided on the basis of septation of spores, *Fusisporium* having non-septate spores, *Fusidium* and *Fusarium* septate spores.

In 1824 Schlechtendahl introduced the use of the curvature of the spores as a character, which was also used by Corda in 1829. The latter distinguished *Fusarium* as having only curved spores and *Fusidium* as having both curved and straight spores. Later, 1837, he changed his views somewhat, giving *Fusidium* only straight spores, and *Fusarium* curved and straight spores, and dropped all forms which had pluri-septate conidia from these genera and used them to establish the genera *Fusoma* and *Selenosporium*, putting them under his *Phragmidiaccae*, while he puts his *Fusidium* and *Fusarium* under the *Caeomaceae*, and *Fusisporium* under the *Sporotrichaceae.*

Fries in 1845 reduced all these forms to two genera, *Fusarium* (Link) and *Fusisporium* (Link), but grouped certain organisms producing sickle-shaped spores in slimy layers into one genus which he called *Pionnotes.*

Saccardo in 1886 divided the genus *Fusarium* into the following subgenera, *Eu-Fusarium*, *Fusamen*, and *Leptosporium* *Eu-Fusarium* was described as having cylindrical, spindle and sickle-shaped conidia with one or more septa, and was subdivided into *Selenosporium* (Corda) and *Fusisporium* (Link). *Fusamen* has similar conidia which are not septate, however, and *Leptosporium* has shorter, ovate or somewhat elongated non-septate conidia. *Fusamen* was divided into *Selenospora* and *Fusispora.*

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* An account of the morphology of the causal organism was submitted as part of a thesis for the M. A. degree from the University of Nebraska in May, 1912, by G. K. K. Link.

Saccardo also defines *Fusidium, Fusoma,* and *Pinnotes;* the former have spindle-shaped straight spores and the latter differs from *Fusarium* in the nature of its spore layers.

Saccardo as well as Lindau and Appel and Wollenweber point out the great disorder and confusion which reign in this realm of mycology. Not only are the species of *Fusarium* not clearly defined, as they are mostly based on host descriptions, but the genus itself is not delineated. In their monograph Appel and Wollenweber 1910 have established the boundaries of the genus using *Atractium* (Link), *Fusidium* (Link), *Fusisporium* (Link), *Selenosporium* (Corda), *Fusoma* (Corda), and *Pionnotes* (Fries) either *in toto,* or in part, as synonyms.*

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* They define (*l. c.* page 61) the genus as follows:

"Konidien mehr oder weniger polar, meist dorsiventral, selten ausgesprochen radiär, mehr oder weniger gekrümmt, in der Reife gewöhnlich septiert, in Massen wenig oder lebhaft gefärbt, mehrere nacheinander an derselben Stelle erzeugt, aber nicht kettenartig verklebt, am Ende einfacher oder verzweigter, septierter Konidienträger, die entweder zerstreut zwischen den Hyphen, gelegentlich zu Coremien vereinigt, oder in Sporodochien gesellig auftreten. Konidien später pulverig zwischen den Hyphen zerstreut oder als tuberculariaähnliches, fest begrenztes, gallertiges Sporodochiumpolster, gelegentlich, als *Pionnotes,* in unbegrenzten schleimigen Lagern auftretend.

"Chlamydosporen, oval oder birnenförmig, einzeln oder gesellig, in Ketten oder Knäueln, dauernd zusammenhängend, terminal oder intercalar, nicht mehrere nacheinander erzeugt, ohne besondere von den Konidienträgern zu unterscheidende Träger, auch in Farbe kaum besonders hervortretend. Nie in gallertigen Lagern dichter zusammengeschart.

"Hyphen septiert, verschieden verzweigt, epi- und endophytisch, spärlich oder reichlich auftretend, entweder isoliert oder zusammen ein lockeres oder dichteres, teilweise zu coremienartigen oder, besonders als Stroma, zu plectenchymatischen gestaltlichen oder gestaltlosen Verwachsungen, ferner häufig auch zu immersem Wachstum neigendes, begrenztes oder ausgebreitetes, vielfach durch Anastomosen innig zusammengeschlossenes, gelegentlich lebhaft gefärbtes Mycel bildend.

"Bemerkung. Es ist unentschieden gelassen, ob Arten ohne Konidienseptierung aus der Gattung ausscheiden, dagegen nicht, wenn sie wenigstens eine Neigung zur Septierung haben *(F. orthoceras),* oder ob erstere sich mit Saccardo zu einer Untergattung *Fusamen* vereinigen lassen; ferner, in welcher Folge die Merkmale für die Bestimmung einer Art als *Fusarium* entscheidend sind, wobei die Wahl ist zwischen: Septierung, Dorsiventralität, Polarität, Längsachsenkrümmung der Konidien. Sehr zweifelhaft erscheint eine Beziehung von *Fusarium* obiger Auffassung mit den von Saccardo unter *Leptosporium* vereinigtene Arten, doch kann nur die Untersuchung vieler Formen diese Frage der Begrenzung des Gattungsbegriffs klären. Was de Farbe der Konidienmassen anbelangt, so scheinen schwarze Farben nicht normal aufzutreten, auch beim Mycel nicht. Helle, Orange und Ockerfarben herrschen bei Konidien vor, für das Mycel treten noch gelb, rot, blau hinzu. Der Begriff Sklerotium ist für *Fusarium* diskutierbar. Die Untersuchungen haben nichts ergeben, was die Sonderstellung irgend welcher plectenchymatischer Gebilde als Sklerotien notwendig erscheinen liesse."

Appel and Wollenweber have worked over a great number of *Fusarium* species and made it their first object to determine which characters in this genus can be used as general, reliable species characters. They also came to definite conclusions concerning the nature of the medium and the cultural conditions which will give these characters most uniformly in their true form and have designated these as "normal" because they offer each *Fusarium* the conditions "Bei der er (der Pilz) im Stande ist, seinen Entwickelungsgang normal abzuschlieszen." They make use of the following characters: form of conidia; presence or absence of chlamydospores; color of the conidia; septation; mycelial color; width of the conidia; and absence or presence of plectenchyma-like stroma masses.

They found that boiled potato tubers and boiled potato stems furnished a normal substratum when kept at a temperature ranging from 12° to 25° C., and in diffuse light.

Cultures grown on gelatin and agar media are not normal and cannot be used in the determination of characters. For the bacteriologist these media have arbitrarily been made normal, but for the mycologist who works with higher fungi they are only of secondary use as Brefeld 1905 points out and as is well borne out by the great masses of conflicting data which have accumulated around many of our species. It is well known that agar colonies often show characters which the fungus ordinarily does not show and that more often not all of the characters of the fungus are realized on these media.

The usual host tissue should be used as much as possible as a substratum, and descriptions should only be made from such cultures. In fact, there is no reason why the mycologist, who works with a vastly more complex mixture than many a chemist does, should not adopt the exact methods of description which the chemist uses. The bacteriologist already has done this. Thus, the normal culture medium for each genus should be determined; and then the nature and kind of the medium and the conditions of light, temperature, and moisture should be clearly stated with each new description of the fungus, so that any one can repeat the work and that all work will be done under the same conditions. This will involve a great deal of labor, but the conditions which will enable us to make determinations of reliable characters of certain complicated genera will have to be determined before much headway can be made. In these studies the characters used by Appel and Wollenweber were employed and the results show that they are reliable characters under the conditions of the experiment. It has also been found that all of these characters can be modified from the normal by variation in the cultural conditions.

Appel and Wollenweber's monograph carries a full bibliography and no attempt is made to duplicate it here. It is evident that if our knowledge of the taxonomy of the genus has been in chaos prior to 1910, the knowledge of the pathological conditions which these organisms bring about has been in no better condition, because the work done cannot be linked to any definite organism and because no reliable isolation and inoculation experiments have been made in many cases.

OCCURRENCE OF THE ORGANISM.

The organism has repeatedly been isolated by the writers from potato tubers affected with dry rot. If the rot has progressed only slightly, a sunken, wrinkled spot appears on the surface of the tuber and usually no exterior signs of the fungus are visible. As the rot progresses the fungus area increases and finally the potato presents a shrunken, wrinkled appearance. Later in the progress of the disease small tufts of hyphae, which are pink in color, may appear on the surface but these should not be called sporodochia (Pl. I).

If one cuts into a partly rotted tuber, a part of the tuber will be found perfectly sound and the other part, which borders on the spot, made up of disintegrated potato tissue, of hyphae and conidia. The potato tissue has a brownish color and is mealy and dry. Here and there large cavities appear, due to rents, which are formed as the cells shrink away from each other, and which are often filled with hyphal masses of a whitish color (Pl. X, fig. 1). When such a potato is cut open and exposed to light the fungus soon takes on a pink color.

If potatoes infected with this organism are kept in rather moist conditions, or if the outer crust is not ruptured, the fungus may eat out the entire contents of the tuber, leaving merely the cork layer (Pl. X, fig. 1). Often pure cultures can be obtained at first trial from such a tuber, because of the fact that the fungus leaves behind itself a crust of hard, dry starch as it makes inroads on the tissue, thus shutting out other fungi. If the wound is open, secondary infections occur, and often bacteria and other fungi, such as *Penicillium* and *Verticillium*, are found with the *Fusarium*. Frequently a wet rot precedes the dry rot if the proper causal bacteria get in (Pl. II). If an inoculation is made by cutting the surface of a tuber and placing the inoculum on it, thus letting the fungus work down and form a crust as it goes, secondary infection rarely sets in. If, however, an inoculation is made by puncturing the skin, thus leaving a hole, bacteria generally get in.

TECHNIQUE.

In their studies Appel and Wollenweber tested all sorts of media and came to the conclusion that the normal conditions for *Fusarium* culture could be realized on sterilized vegetable substrata. They used as much as possible the tissues of the host on which the fungus is found.

In the course of these studies with *Fusarium tuberivorum*, sterilized potato plugs, sterilized potato stems, raw potato plates, glucose agar, beef bouillon (+10), sawdust soaked with potato-vine extract, filter paper soaked with a synthetic solution of the same composition as the glucose agar, and potato agar were used as solid culture media. Various liquid media, such as glucose solution and water, were used.

The plugs were prepared from potato tubers grown under irrigation and put into Roux tubes whose container was half filled with water. The tubes were then plugged and sterilized by steaming on three consecutive days at 100° C. The first day they were steamed for a period of one-half hour and on the other days for a period of 15 minutes. Pieces of young potato vines were prepared in the same manner.

The glucose agar used was of the same composition as that used by Appel and Wollenweber with the exception that 15 grams of agar were used instead of 10 grams.

The following is the formula for the agar:

1,000 c.c. water.
20 grams ammonium nitrate.
10 grams di-potassium phosphate.
5 grams magnesium sulfate.
100 grams glucose.
15 grams agar (Witte's powdered).

The chemicals were Merck's and chemically pure. The agar was dissolved in the water, autoclaved and then the other ingredients were added and the solution sterilized on three consecutive days at 100° C. in streaming steam.

Cultures were also grown in hanging drops of agar prepared in the above manner and in distilled water. By using these drops we were enabled to study the progress of a single spore's development for nine days. Some cultures were also grown in Erlenmeyer flasks in distilled water, 1 per cent glucose, and in a solution of the following composition:

1,000 c.c. water.
20 grams ammonium nitrate.
10 grams di-potassium phosphate.
5 grams magnesium sulfate.
100 grams glucose.

A few cultures were grown on filter paper soaked with a 1 per cent glucose solution. A potato agar of the following composition was used:

500 c.c. water.
100 grams glucose.
500 grams potato extract.
15 grams agar.

Potato plugs, raw potato plates, and stems were used for the determination of the morphological characters; while the agar was used for the isolation, for color study, and for the study of the rapidity of growth of the organism. The liquid media were used for color study and for spore study.

The growth of the fungus was studied at the following temperatures and humidities (the humidities given being those of the air which surrounded the tubes or plates in question):

8° to 10° C., (humidity 60 per cent); 25° to 27° C., (humidity 98 per cent); 20° to 25° C., (humidity 40 to 55 per cent); 22° to 35° C., (humidity 40 to 55 per cent); 25° to 45° C., (humidity 10 to 40 per cent); 1.1° C., —3.9° C.; and —22° C.

Cultures were grown in direct sunlight, in diffuse light, in darkness, and under double walled bell jars filled with solutions of copper sulfate and ammonium hydrate, and potassium bichromate prepared according to Bulletin 55 of the Bureau of Plant Industry, page 49. Cultures in the dark were made by wrapping the Roux tubes with the black paper which is used in wrapping photographic plates.

The original isolation was begun by opening an infected tuber and cutting out pieces of the tissue near the affected area with sterilized needles. These pieces were then transferred to agar plates and no contaminations of any sort appeared. When the spore material was examined it was apparent either that there were six to eight types of *Fusarium* in the culture or that it was a pure culture showing a great diversity as to spore form. Consequently it was absolutely necessary to isolate single spores and then grow these to determine whether these spore forms were all from one progenitor or from several.

Various methods were employed by the writers for single spore isolation; but none, save one by which they could actually examine the inoculum before inoculation and determine whether a single spore was present or not, is satisfactory and reliable The use of the ordinary dilution and pouring method is admissible after one has pure cultures and when the spores do not stick together. The same thing applies to the streak plate method. The examination of poured plates is a cumbersome and inadequate method if one has to determine positively whether one is dealing with single spores or not. The writers found that the following method is quite easy, absolutely safe, and rigidly scientific: A small amount of culture material is put into about 1 c.c. of sterilized water and then well shaken and stirred. The suspension is then poured into a petri dish, and a few drops about the size of a pin point, which are removed with a platinum wire with a minute loop, are examined and the spore content determined. If so dilute that one gets one or no spores, single drops are then put upon sterile cover-glasses and examined on a sterile hanging drop slide with the microscope. If a spore is present, the cover-glass is transferred to an agar plate by shoving it into the agar medium, drop side up, until the drop touches the surface of the medium. A little sterilized water is then poured on the agar, and the plate covered and rolled so as to distribute the suspension. If this work is done in an inoculation cage* and if one works cleanly and carefully, it can be done without danger of contamination. If contaminations do set in, transfers are made as soon as the colonies appear, and in this manner absolute single spore cultures are gotten. Plantings made in this manner when more than one spore was counted in the drop show the required number of colonies. The contaminations which ordinarily appear are *Mucor*, *Penicillium*, and *Aspergillus*.

If one allows the spores to germinate in the petri dish before the actual mounts are made, detection of the spores under the lens is facilitated, and in this manner the smallest of spores can be found. Sooner or later all who expect to have *pure cultures* which are really pure cultures will have to follow the advice of Brefeld (14:87).†

The color determinations were made according to the Repertoire de Couleurs published by the Société Francaise des Chrysanthemists 1905.

MACROSCOPIC CHARACTERS.

Studies for the determination of the gross aspect of the fungus were made with cultures on glucose agar and on beef bouillon.

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* Wilcox, E. M., and Link, G. K. K. 1912. A new form of pure culture chamber. Phytopathology 2:120. Fig. 1.

† "Für die Durchführung zuverlässiger mycologischer Untersuchungen ist die Gewinnung des Sporenmaterials von den verschiedenen Pilzen in reiner Form das erste und unerlässlichste Erfordernis. Von dem reinen Sporenmaterial kann nur durch die Aussaat der einzelnen Spore und ihre continuierliche Verfolgung in allen Stadien der Entwicklung in den geeigneten, durchsichtigen pilzfreien Nährmedien ein sicheres Resultat gewonnen werden, welches in den einzelnen Fällen der weiteren Ergänzung bedarf durch die Aussaat rein gewonnenen Sporenmaterials in sichersterilisierten und zusagenden, nach aussen geschützten Massensubstraten."

In these the growth of the fungus at first is appressed, appears white in color, and the edge of the colony is marked by a fluffy, white, aerial mycelium. This fluffy edge is characteristic of cultures thruout their entire development. The central part of the colony produces conidia first on aerial hyphae, which soon collapse and allow the conidia to fall on the hyphal mat and give it a pink color. If secondary germination of conidia sets in, the whole mass is covered by another mat of aerial hyphae, which often do not go over to conidia formation, and consequently the culture looks more white than it normally does. When the culture has been under favorable conditions of light and moisture, an enormous number of conidia are formed, which fall down to the substratum, so that we get concentric rings of heaps of hyphae and conidia, which look like series of embankments (Pl. XXII). The whole colony appears powdery after two weeks' growth. In the agar a very firm plectenchyma is formed, which sets up tensions, pulling the mass into wrinkles as it grows older. No stroma-like or sclerotial bodies are formed.

On some potato tubes masses of mycelium which were black or dark blue in color were formed if the oxygen supply was cut down. According to Appel and Wollenweber the appearance of sclerotia need not be considered as a taxonomic character. They are by far not as pronounced in *Fusarium tuberivorum* as they are in *Fusarium orthoceras* according to Appel and Wollenweber's and the writers' observations.

THE MYCELIUM.

In this organism we have to consider a complex of hyphal threads. Under proper conditions the hyphae fragment terminally into colonies of cells, usually called spores or conidia, which may be made up of from one to eight cells. That we have colonies is indicated by the fact that these spores break up into oidia when put into unfavorable conditions such as are realized when the fungus is grown on beef bouillon or in distilled water. On beef extract the mycelium itself can be made to fragment intercalarally into such colonies. Such fragments, however, do not show the end differentiation which the end cells of the usual colony do. At times, in tube cultures, and in distilled water, the mycelium fragments terminally or intercalarally into round, thick walled, simple, or compound colonies which usually are smooth and full of oil. On raw potato plates such colonies with spiny walls were noted and these can be called chlamydospores.

Under other conditions the mycelium vegetates as such without spore formation, especially if the temperature is low and if there is an abundance of food. The same condition was realized in cultures in 1 per cent glucose solution and in distilled water. In the former case there probably is so much food that the mycelium can maintain its growth without going over to spore formation, while in the latter the growth is so slow and impoverished that septation cannot set in.

Spores are borne on conidiophores of varying complexity. Generally the conidiophores are arranged on one side of a hypha and are simple, unbranched, one to several celled, sterigma-like structures. A compound tristerigmate conidiophore has been found, and all gradations between this and the simplest have been obtained by varying the cultural condition.

The fungus on its natural host makes a loose growth and takes the form of an aerial mycelium when it has access to cavities. Before the cavities are entirely filled, and in moist tube cultures, the peculiar arrangement of the hyphae which puts this fungus under the *Tuberculariaceae* is very apparent.

No sporodochia-like structures are found on agar at all. At times on agar, especially if a little normal lactic acid has been added to it, a slimy *Pionnotes* appearance is realized. This has also been found off and on on glucose agar.

SPORE SEPTATION.

Counts of spores and measurements were made from cultures all of which had been started from the same spore and grown under various environmental conditions. All of the detailed study was made with the progeny of a single, three-septate, curved spore. This course was adopted only after the writers had satisfied themselves from studies of colonies which had come from 50 single spores that they all behaved alike. It makes no difference whether a single celled spore is used or a three-septate spore, the results are the same. A three-septate curved spore was used so that the variations which do appear might be as apparent as possible and because there can be no doubt that such a spore is a true *Fusarium* spore.

These studies were made with cultures which were grown on potato plugs in an incubator, temperature 25° to 27° C., (humidity 98 per cent), wrapped in black paper, in a refrigerator, temperature 8° to 10° C., (humidity 60 per cent), wrapped in black paper, in the room in diffuse light, and in the room, wrapped in black paper, temperature 20° to 25° C., (humidity 40 to 60 per cent). From these cultures counts were made every week for four weeks to determine the fluctuation of the number of septations per spore. These results are plotted in curves, Tables 2 to 5, Graphs 1, 2, 3, and 4. Besides these tabulated counts, several hundred were made from cultures on potato plugs, agar, and raw potato, and all show a great preponderance in the number of the one-septate spores. This number ranges from 40 to 98 per cent according to the age of the culture, the one-septate spores increasing in number while the two- and three-septate spores decrease in number with the aging of the colony.

The results show that for a definite medium under definite conditions the percentages of the number of septations are a reliable character. Appel and Wollenweber distinguish an "An," "Norm," and "Ab-Kultur" and a "Jung," "Hoch," and "Alt-Kultur." The conidia which are produced from the mycelium of an original isolation inoculation would be "An-Kultur" conidia. These are unfit for character studies. When such conidia of the "An-Kultur" are used as inoculum, the resulting culture is a "Norm-Kultur," which can be maintained for a long time by repeated transfers. If degeneration should set in, the "Ab-Kultur" condition would result. They divide the "Norm-Kultur" into "Jung," "Hoch," and "Alt-Kultur." In the former the conidia may be abnormally large or small and irregular in form, consequently not suitable for measurements and form study. In the "Hoch-Kultur," which sets in after a period of eight to fourteen days, the greatest uniformity is noticed and this condition may last for a month. Poorly developed forms which develop late in the "Norm-Kultur" constitute the "Alt-Kultur."

No striking differences in the appearance of the conidia were found in the various cultural stages of *Fusarium tuberivorum* excepting poorly developed conidia which can be placed in the "Alt-Kultur." All of the work was done with the organism in the "Hoch-Kultur" condition so that there might be uniformity in the data. In the "Alt-Kultur" the spores dry up, curve considerably, and often one end cell becomes very pointed and hyalin. When this condition is reached the percentage of one septate conidia is very high, 85 to 95 per cent. At times cells of such a spore seem to have varying amounts of plasma, one remaining plump and round and the other drying up and becoming pointed.

The percentages of numbers of septation per spore are surprisingly constant, but can be influenced by changes in the environmental conditions. Especially is this the case when the temperatures are varied. (Tables 2 to 5, Graphs 1 to 4.)

Counts have repeatedly been made of the number of spore septations of *Fusarium orthoceras*, of *Fusarium tuberivorum*, and of what may be another *Fusarium* which attacks Colorado potatoes, and we find that for these three species the counts of the number of septation of the spores would be sufficient to separate them. When in addition one makes use of other characters there can be no reason why the characters decided upon by Appel and Wollenweber should not give a good working basis for the genus.

In this fungus not much difference can be noticed in the rapidity of the growth of the cultures, whether one begins with conidia or with mycelium as inoculum. It was noted that a 15-months-old culture on rice which was as dry as powder gave viable conidia, which had not at all lost their pathogenesis for tubers.

The spore walls are quite thick. Single-celled or two-celled colonies are by far more resistant to collapse of the wall than those of a higher number of cells; in fact it seems probable that the walls which set in in a growing cell are a response to a pressure stimulus. The diameter of septa suffers practically no shrinkage even under the driest condition and consequently gives a very constant and reliable basis for measurement. When the cell wall of a spore collapses, the spore looks very much like a series of hourglasses (Pl. XXVII, figs. 14-15, 20, and 22).

When the fungus is grown on agar, the cells swell greatly while the septa do not, and then we get a spore which looks very much like an inflated rubber tube constricted by bands at regular intervals. Sometimes these appear in colonies on agar and are then associated with a slimy appearance so that one could easily mistake them for a new species or for a subspecies. In fact, both the dried-out form and this swollen form have off and on been described as new species.

If the spores figured by Appel and Wollenweber 1910, page 38, as *Fusarium didymum* were bent slightly on the cross wall as an axis, and if one end were bent a trifle more than the other, we would have a spore such as presented by *Fusarium tuberivorum.* In the one-septate spores one end usually is a little more plump than the other. Some of these spores, however, show a true sickle shape. By far the most spores in the pure cultures, even as many as 98 per cent, are one-septate. At times the basal ends show remnants of the so-called foot, but it is a very difficult matter to decide which end is basal or apical after the spore is once off the sterigma.

Some of the higher septate spores show the shape of *Fusarium coeruleum*, others that of *Fusarium* sp. (Appel and Wollenweber 1910, fig. S, page 38). A combination of *Fusarium coeruleum* and of *Fusarium solani* would in many cases give us the shape of the typical spore of *Fusarium tuberivorum.* Often the nonseptate spores are clavate. This condition is very frequently found on beef bouillon or in cultures which have been grown in distilled water (Pl. XXVII, fig. 13). When colonies or spores are put into water all of the spores are of the clavate shape.

There is a great range in the form of these spores. A spore may have an almost straight ventral axis and a dorsal axis with a curvature like that of *Fusarium* sp. (See figure 8, page 38 of Appel and Wollenweber 1910 and Pl. XXIV, figs. 30, 33, 34, 45, 51, 57, and 60 of the present bulletin), or it may have a ventral axis which is straight up to the last septum at the apex and then bends in the same manner as does *Fusarium solani* (Pl. XXIV, fig. 4), and a dorsal axis which is decidedly more humped at the two apical septa than is that of *Fusarium solani* (Pl. XXIV, fig. 40; Pl. XXIII, figs. 3, 4, and 9).

That the spores can develop a specialized apical and basal cell is shown by cultures which were made on potato plugs grown at the temperatures 8° to 10° C. Growth was very slow under these conditions and the percentage of three-septate spores, which ordinarily does not run over 10 per cent, went up to 40 per cent. The spores remained attached to the conidiophore for a long time, developed slowly, and showed all stages in the development of the peculiar structures which we find on the apical and basal cells of a spore.

The apical cells show a tapering such as *Fusarium discolor* and *Fusarium rubiginosum* do, excepting that the end is a little more blunt than in the former (Pl. XXIII, fig. 18). The basal cells show all gradations in the development of the foot or "Stiefel." Practically all the types are found here. Hanging drop cultures show that the elongation of the apical cell is determined before it gets to be a conidium, *i. e.*, when the basal cell of the preceding conidium is developed. There is a pulling of each end much like the pulling of wax, causing the basal end of the conidium to taper in the opposite direction. In rapidly-developing conidia the cell rounds off quickly and is cut off so quickly that these peculiar end structures are not developed. This is a predominating condition in the spores of *Fusarium tuberivorum*. When the medium becomes exhausted or when a fungus develops slowly and has an opportunity to mature before it germinates, the end cells are developed.

The origin of the little papillae-like structures which are apparent as a heel of the boot has been nicely indicated. Appel and Wollenweber 1910 in fig. 8, 2, page 38, figured a spore with two such papillae. *Fusarium didymum* shows traces of these, and all the others show various stages of degeneration of these papillae. When the organism is grown in beef bouillon, fragmentation of these colonies sets in so slowly that the origin of these swellings becomes apparent. They are remnants of the outer walls which are left as two adjoining spores separate by their cross walls. Cells separate last in the middle of the septa, thus producing a pulled out appearance (Pl. XXV, figs. 2, 4, 5, and 7). This last point of contact gives rise to the toe, one edge formed by the wall to the foot, and the other edge is usually lost (Pl. XXV, figs. 2, 4, 5, and 7), but retained in such spores as we find in figures S and L on page 38 of Appel and Wollenweber 1910. Slow growth favors the development of these parts, while in rapid development they are lost. The one- and non-septate spores which are developed rapidly show no such modification. In general we do not find that the structure of the basal and apical cell of this species develops anything that can be considered sufficiently characteristic to be used as a specific character. All sorts of stages are shown in the plate, so that each one can judge for himself, as it is possible that one who has studied a great number of species of *Fusarium* will be able to pick out the characteristic form which can be set aside for this particular species.

The following are some counts of spores from a culture:

On glucose agar, 115 days old, dry.

0-septate	1 per cent.
1-septate	98 per cent.
2-septate	1 per cent.
3+-septate	Very few.

On potato plugs in Roux tubes, some water left in the bulb, 130 days old, ochre-color.

0-septate	Few.
1-septate	98 per cent.
2-septate	Few.
3-septate	Very few.

In refrigerator, potato plugs moist, temperature 8° to 10° C., humidity 60 per cent, 70 days old.

0-septate	20 per cent.
1-septate	55 per cent.
2-septate	10 per cent.
3-septate	13 per cent.
4-septate	3 per cent.

0-septate	18 per cent.
1-septate	71 per cent.
2-septate	10 per cent.
3-septate	1 per cent.
4-septate	Few.

The average of six tubes which were partly dry and partly moist was:

0-septate	18 per cent.
1-septate	64 per cent.
2-septate	12 per cent.
3-septate	5 per cent.
4+-septate	Few.

In incubator, potato plugs moist, temperature 25° to 27° C., humidity 98 per cent, 70 days old.

0-septate	7 per cent.
1-septate	82 per cent.
2-septate	8 per cent.
3-septate	2 per cent.
4+-septate	Few.

Potato plug dry.

0-septate	2 per cent.
1-septate	71 per cent.
2-septate	20 per cent.
3-septate	5 per cent.
4+-septate	Few.

Average of six tubes.

0-septate	4 per cent.
1-septate	80 per cent.
2-septate	12 per cent.
3-septate	4 per cent.

Tubes wraped in black paper, potato plugs dry, temperature 22° to 25° C., humidity 40 to 55 per cent, 70 days old, in room.

0-septate	Few.
1-septate	98 per cent.
2-septate	2 per cent.
3+-septate	Few.

Potato plug wet.

0-septate	5 per cent.
1-septate	77 per cent.
2-septate	13 per cent.
3-septate	5 per cent.
4+-septate	Few.

Potato plug always dry.

0-septate	Few.
1-septate	98 per cent.
2-septate	Few.
3-septate	Few.

Grown in distilled water, temperature 25° to 27° C., 8 weeks old, in light and in dark; few spores.

0-septate	99 per cent.
1+-septate	Exceedingly few.

Grown in 1 per cent glucose, immersed, 4 weeks old, no conidia.

From raw potato, culture dry, 150 days old, ochre-color.

0-septate	23 per cent.
1-septate	69 per cent.
2-septate	7 per cent.
3+-septate	1 per cent.

0-septate	30 per cent.
1-septate	67 per cent.
2-septate	2 per cent.
3+-septate	Few.

Averages from a great number of potatoes taken at random, counted at different times, gave the following results:

0-septate	9 per cent.
1-septate	85 per cent.
2-septate	5 per cent.
3+-septate	Few.

Grown on glucose agar, 4 days old.

0-septate	20 per cent.
1-septate	70 per cent.
2-septate	8 per cent.
3-septate	2 per cent.
4+-septate	Few.

Same culture 52 days old.

0-septate	7 per cent.
1-septate	84 per cent.
2-septate	10 per cent.
3+-septate	Few.

On stems 7 days old, in light.

0-septate	16 per cent.
1-septate	49 per cent.
2-septate	23 per cent.
3-septate	11 per cent.

On stems 48 days old, dry, in light.

0-septate	10 per cent.
1-septate	81 per cent.
2-septate	9 per cent.
3+-septate	Few.

TABLE 2.—*Representing in percentages the fluctuation of spore septation of a culture grown in a refrigerator, temperature 8° to 10° C., humidity 60 per cent.*

		February 16	February 23	March 1	March 8
0-septate.	Tube A	0	17	15	32
	B	7	8	10	12
	C	0	3	3	7
	D	2	3	9	17
	Average	2	8	9	17
1-septate.	Tube A	29	51	57	56
	B	30	40	43	53
	C	30	47	43	61
	D	18	46	60	74
	Average	27	46	51	61
2-septate.	Tube A	27	19	16	7
	B	25	21	21	18
	C	28	18	15	20
	D	20	19	16	6
	Average	25	19	17	13
3-septate.	Tube A	44	12	12	5
	B	36	31	26	17
	C	42	32	39	12
	D	54	32	15	3
	Average	44	27	23	9
4-5-septate.	Tube D	7			

TABLE 3.—*Representing in percentages the fluctuation of spore septation of a culture grown in an incubator, temperature 25° to 27° C., humidity 98 per cent.*

		February 16	February 23	March 1	March 8
0-septate.	Tube A.	35	5	8	5
	B.	5	6	16	26
	C.	12	7	6	41
	D.	17	15	23	15
	Average	17	8	13	22
1-septate.	Tube A.	57	85	83	80
	B.	77	90	66	72
	C.	67	80	84	56
	D.	77	76	75	85
	Average	67	83	77	73
2-septate.	Tube A.	8	6	8	12
	B.	16	4	13	2
	C.	9	9	6	3
	D.	8	5	1	0
	Average	10	6	7	4
3-septate.	Tube A.	0	4	1	3
	B.	2	0	5	0
	C.	12	4	4	0
	D.	5	4	1	0
	Average	5	3	3	1

TABLE 4.—*Representing in percentages the fluctuation of spore septation of a culture grown in a room, temperature 20° to 27° C., humidity 40 to 55 per cent.*

		February 16	February 23	March 1	March 8
0-septate.	Tube A	8	12	7	17
	B	5	12	2	9
	C	5	....	11	
	D	8	4	10	
	Average	7	9	8	13
1-septate.	Tube A	68	79	88	78
	B	72	76	83	81
	C	73	....	77	
	D	88	82	82	
	Average	75	79	83	80
2-septate.	Tube A	18	6	3	5
	B	13	8	10	7
	C	13	..	10	
	D	1	13	7	
	Average	11	9	8	6
3-septate.	Tube A	6	3	2	
	B	10	4	5	3
	C	9	....	2	
	D	3	1	1	
	Average	7	3	3	1

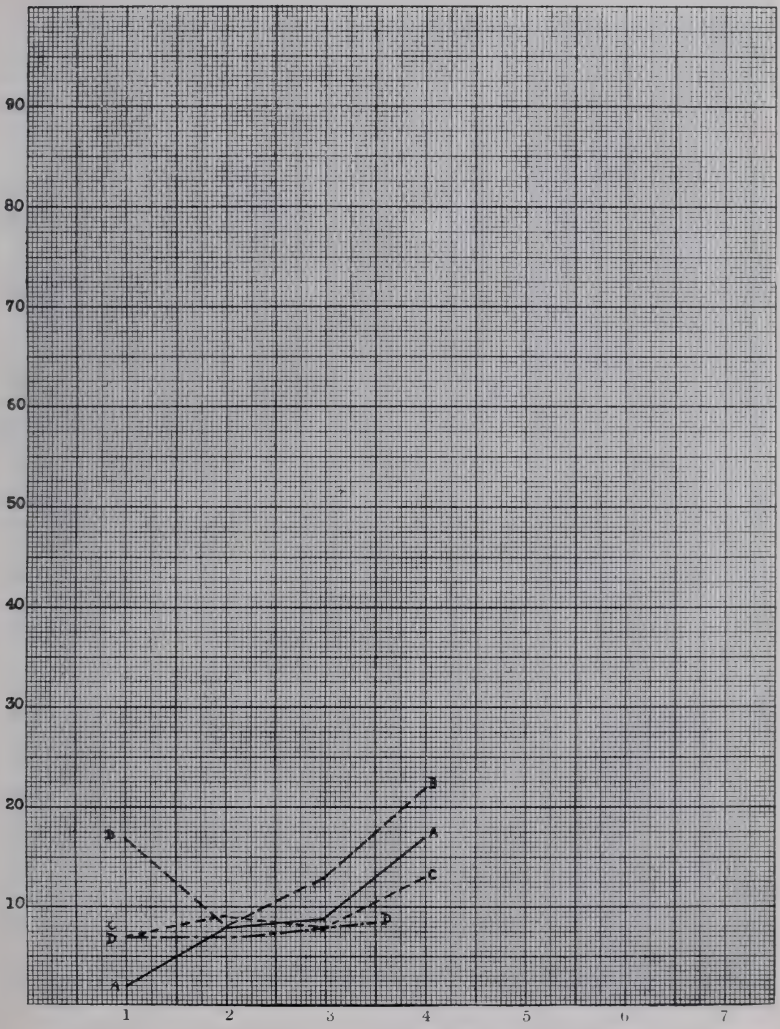
TABLE 5.—*Representing in percentages the fluctuation of spore septation of a culture wrapped in black paper, grown in a room, temperature 20° to 27° C., humidity 40 to 55 per cent.*

		February 16	February 23	March 1
0-septate.	Tube A	5	7	6
	B	4	8	9
	C	12	8	10
	D	7	6	6
	Average	7	7	8
1-septate.	Tube A	79	82	85
	B	78	79	87
	C	85	79	75
	D	70	79	82
	Average	78	80	83
2-septate.	Tube A	14	7	8
	B	9	11	2
	C	2	6	9
	D	13	11	10
	Average	10	9	8
3-septate.	Tube A	2	4	1
	B	9	2	1
	C	1	7	6
	D	10	4	2
	Average	6	4	3

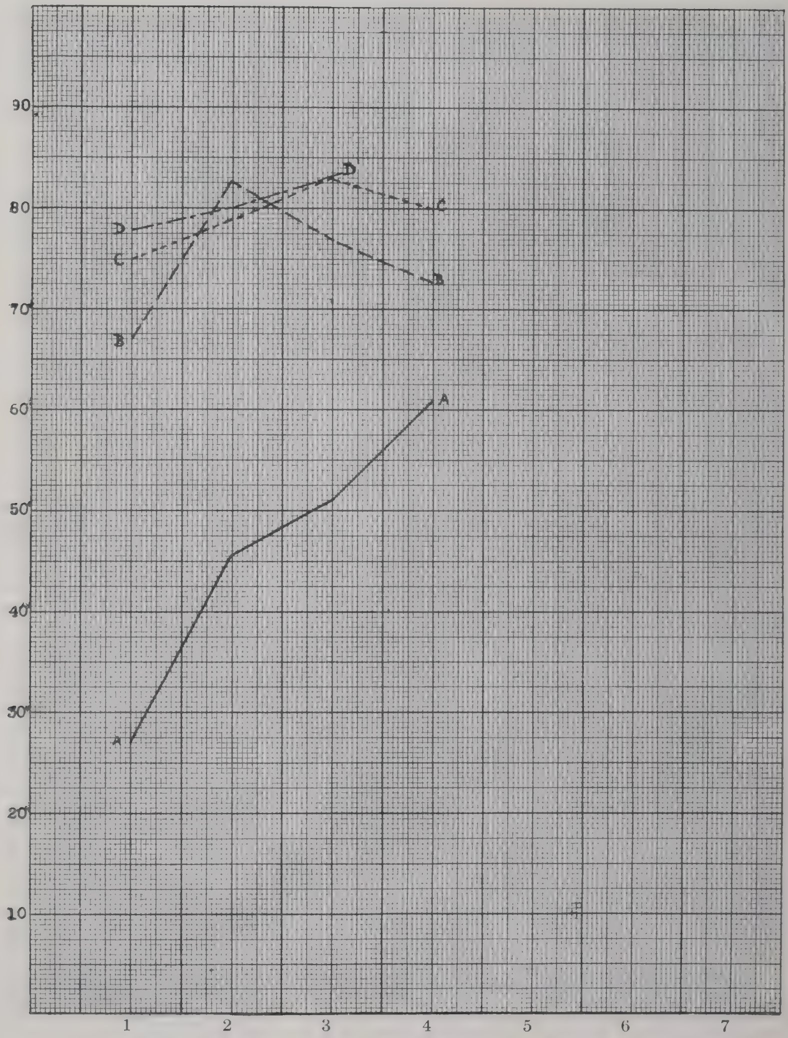
In these tables each figure represents the average of at least six counts. The cultures studied in this case were started with inoculum from a culture which had been started with a single three-septate spore, five weeks old, and showed the following percentages of spore septation:

0-septate	6 per cent.
1-septate	83 per cent.
2-septate	9 per cent.
3-septate	2 per cent.

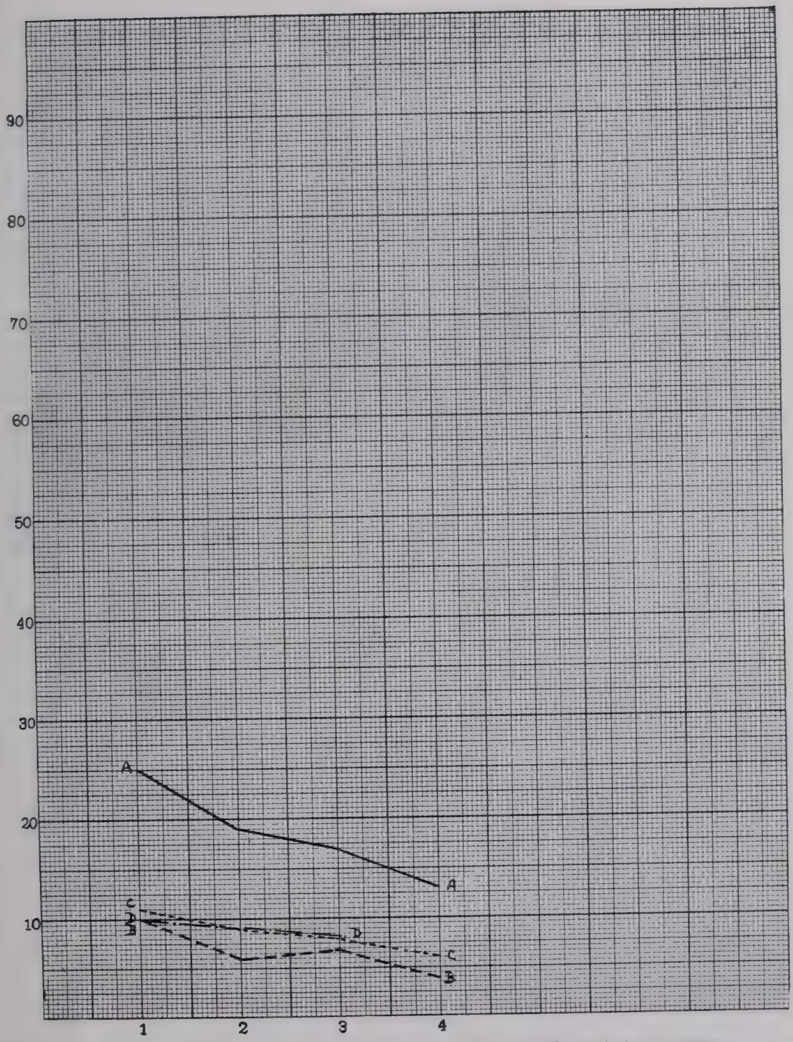
Graphs 1, 2, 3, and 4 are plots of the figures represented in Tables 2, 3, 4, and 5. The percentages are plotted on the ordinates and the number of weeks on the abscissae. In each graph, line A represents the cultures grown in the refrigerator, line B the cultures grown in the incubator, line C the cultures grown in the room, and line D the cultures wrapped in black paper and grown in the room.



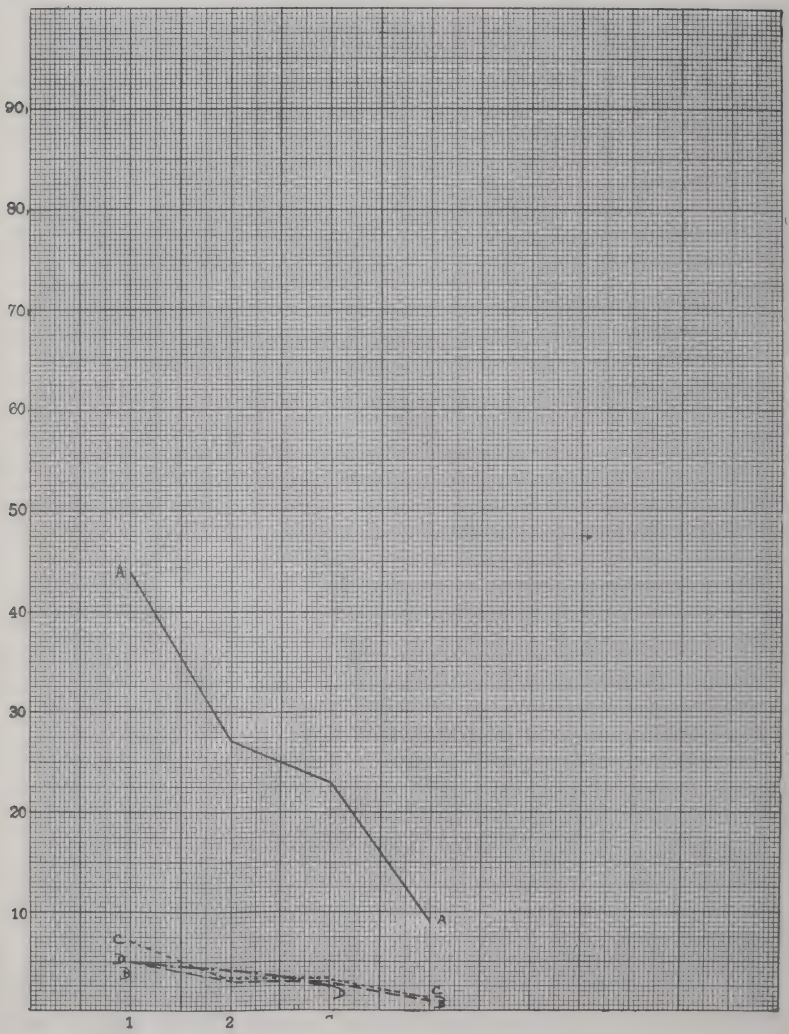
Graph 1. Fluctuation in the number of non-septate spores.



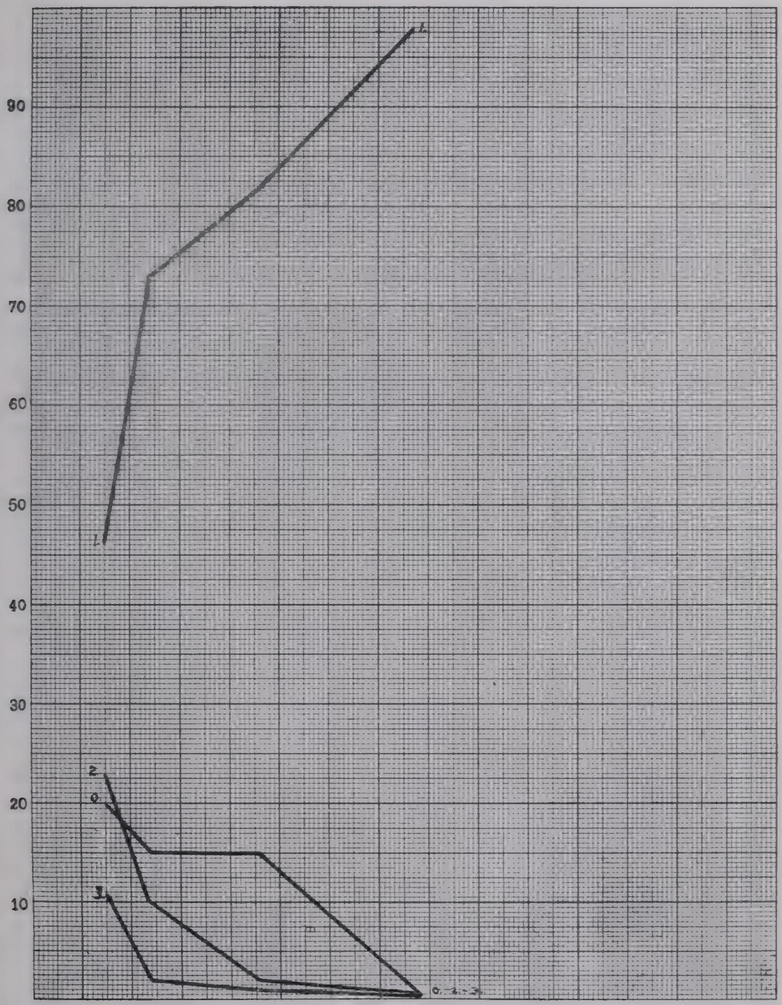
Graph 2. Fluctuation in the number of 1-septate spores.



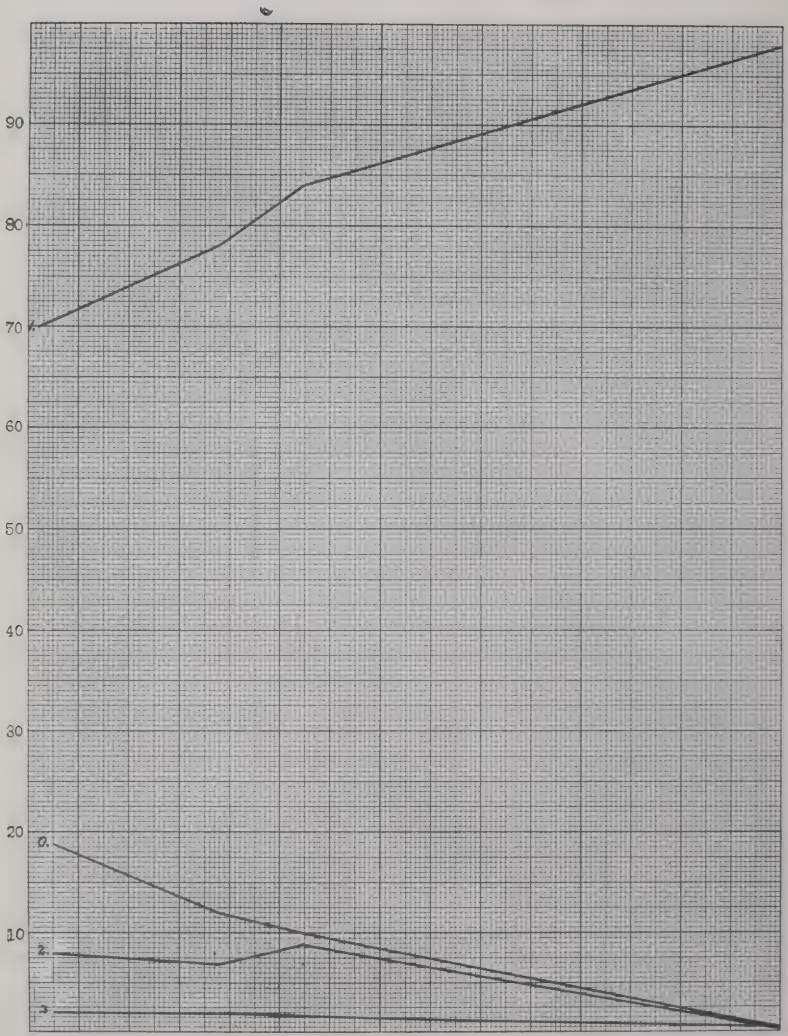
Graph 3. Fluctuation in the number of 2-septate spores.



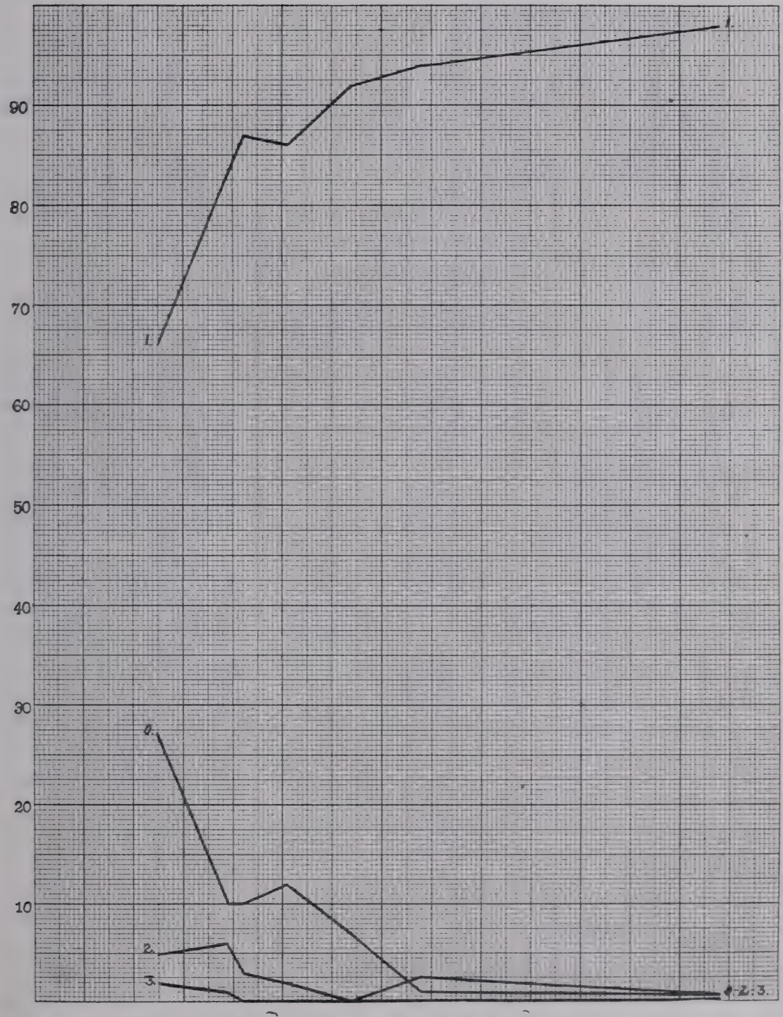
Graph 4. Fluctuation in the number of 3-septate spores.



Graph 5. Fluctuation in spore septation of culture grown on potato stems for seventy-eight (78) days.



Graph 6. Fluctuation in spore septation of culture grown on glucose agar for one hundred and fifty (150) days.



Graph 7. Fluctuation in spore septation of culture grown on potato plug for one hundred and thirty-eight (138) days.

Graph 1 represents the fluctuation in the number of non-septate spores, Graph 2 the fluctuation in the number of one-septate spores, Graph 3 the fluctuation in the number of two-septate spores, and Graph 4 the fluctuation in the number of three-septate spores. Graph 5 represents the fluctuation in the number of spore septation of a culture made from the same inoculum as cultures of Graphs 1, 2, 3, and 4 and grown on potato stems for 78 days. Counts were made when the culture was 15, 24, 47, and 78 days old. Graph 6 represents the fluctuation in the number of spore septation of a culture made from the same inoculum as cultures for Graphs 1, 2, 3, and 4, grown on glucose agar for 150 days. Counts were made when the culture was 5, 37, 55, and 150 days old. Graph 7 represents the fluctuation in the number of spore septation of a culture made from the same inoculum as the culture for Graph 6 and grown on a potato plug for 138 days. Counts were made when the culture was 25, 39, 65 and 130 days old.

In Graphs 5, 6, and 7 each space on the abscissa represents one day and every two spaces on the ordinate one per cent. Lines 0, 1, 2, and 3 represent the number of 0-, 1-, 2-, and 3-septate spores respectively.

From these graphs it is apparent that the number of 1-septate spores increases with the age of the culture and that the number of 2- to 3-septate spores decreases. This holds for all sorts of media and substrata. It also is apparent that light has little influence on the percentages, at least not more than the error of the count, that moisture has some influence and that temperature, especially low temperature, has the most decided influence. Low temperatures retard growth, consequently a spore is slowly cut off, does not germinate into a hypa at once, but rather grows slowly and becomes septate. The multicellular spore is really only a slow or delayed form of germination of a single celled spore or true conidium. Observations of single-celled spores show that they are just as able to germinate as any other. The many-celled spores when put into water break up into their component parts which can germinate under proper conditions.

As the food supply becomes exhausted, and this is soon realized on the outside of the mat of a colony, the 2- to 3-septate condition drops off and the 1-septate condition runs up to 90 to 98 per cent. In tubers, when the fungus has sufficient food but where a sudden check is put on growth due to desiccation, the percentages of non-septate spores run high. The spores ordinarily fall off the sterigmata when in the non-septate condition; often, however, especially if growth is slow, several septa may appear before the spore falls off. Under favorable conditions a single-celled spore is formed, the sterigma grows rapidly and shoves the spore off. If sufficient food is present, the spore germinates at once either into a hypha or into a several-septate spore. Under the most favorable conditions, however, the spore germinates at once into a hypha. When the food supply gives out, the one-septate condition is the most prevalent and, as mentioned above, many of these spores show only one viable end. At times the spores germinate directly into other conidia (Pl. XXVII, figs. 23 and 24). Very often the conidia fuse and then we have an appearance like that presented by the basidiospores of *Tilletia,* joined up and producing other conidia (Pl. XXVII, fig. 10). Fusions in the mycelium are often found.

INFLUENCE OF TEMPERATURE.

As mentioned above, temperature has a decided influence on the septation of the mycelium. The fungus grows best at temperatures ranging from 22° to 27° C. Temperatures above this retard the growth, and when the organism is subjected to temperatures ranging from 40° to 55° C., no growth sets in. At 1° C., —22° C., and —3.9° C. no growth takes place, but when the fungus which was kept at 1° C. for a period of three weeks is brought into a temperature of 3.3° C., growth begins, and when the cultures were kept at —22° C. and —3.9° C. for two weeks and then gradually brought up to the temperature of 3.3° C., no growth was noted. When these were put into a temperature of 30° C., growth set in at once. The fungus which had been kept at the lowest temperature made the fastest growth when it was removed to higher temperature. A temperature ranging from 8° to 10° C. is only slightly inhibitive to growth and when potatoes infected with the organism are stored at this temperature the most rapid decay takes place provided the air is quite moist.

TABLE 6.—*Morphogenic and chromogenic influence of factors.*

	April 1	April 3	April 4	April 5	April 6	April 8	April 10	April 14
In sunlight, temperature 30 to 40° C. and 20 to 30° C.	....	3.3x3.3 cm., very pink, fluffy edge.	4x4 cm., fluffy, white edge, pink in middle	5.5 x 5.5 cm., fluffy edge, appearance of concentric rings.	6.5 x 6.5 cm., very pink.	7.5x7.5 cm., very pink.	8x8 cm., very pink, powdery.	9.5x9.5 cm., very pink.
In diffuse light, temperature 25 to 30° C., humidity 40 to 50 per cent.	3 mm., appressed.	3x3 cm., appressed, powdery, fluffy tendency, white.	4x4.5 cm., powdery, fluffy, pink.	5.5 x 5.5 cm., fluffy edge, secondary whiteness appearing in middle.	6.5 x 6.5 cm., white, fluffy.	8.5 x 8.5 cm., pink, somewhat white, fluffy.	9.5 x 9.5 cm., pink.	9.5x9.5 cm., very pink.
In dark, temperature 25 to 30° C., humidity 40 to 50 per cent.	.5x.5 cm., powdery edge, pink middle.	3.5 x 3.5 cm., powdery, pink, fluffy edge.	4.4 x 4.5 cm., very pink.	5.5 x 5.5 cm., copious fluffiness in middle.	7.5 x 7.5 cm., fluffy.	8x9 cm., powdery, pink.	8.5 x 9.5 cm., fluffy covering.	9.5x9.5 cm., fluffy covering.
In dark, temperature 10 to 15° C., humidity 60 per cent.	Slight growth	.5x.5 cm.	2 x 2.5 cm., white.	3x3 cm., white, powdery, slight pink, sparse growth	4x4 cm., white.	5.5 x 5.5 cm., slight pink.	6.5x7 cm., fluffy, pink.	8.5x8.5 cm., fluffy, pink.
In dark, over H_2SO_4, temperature 25 to 30° C., in petri dish.	.5 x .5 cm., appressed	3x3 cm., fluffy white.	4x4 cm., fluffy, pink.	5.5 x 5.5 cm., exceedingly fluffy.	7x7 cm., powdery. Cover removed.	8x7.5 cm., powdery.	8x7.5 cm., powdery.	8x7.5 cm., powdery.
Some of these plates removed to incubator, humidity 98 per cent.	....	....	....	....	Some plates put into incubator.	....	9.5 x 9.5 cm., pink, fluffy.	9.5x9.5 cm., pink, fluffy.

TABLE 6.—*Morphogenic and chromogenic influence of factors—Concluded.*

	April 1	April 3	April 4	April 5	April 6	April 8	April	April 14
In red bell jar, temperature 25 to 30° C.	....	3x3 cm., white, powdery.	4.5 x 4.5 cm., powdery, quite pink, more than in blue.	6.5 x 6.5 cm., very white and fluffy.	7.7 x 7.7 cm., white.	9.5 x 9.5 cm., pink, fluffy.	9.5 x 9.5 cm., pink, fluffy.	9.5x9.5 cm., pink, fluffy.
In blue bell jar, temperature 25 to 30° C.	....	4x3 cm., fluffy at edge, white middle.	5.5x5.5 cm., pale pink, fluffy.	6.5 x 6.5 cm., fluffy edge, pink in middle	8x8 cm., pink, covered by loose white mycelium.	9.5 x 9.5 cm., very pink.	9.5 x 9.5 cm., very pink.	9.5x9.5 cm., very pink.
In dark, humidity 98 per cent, temperature 25 to 27° C.	.5x.5 cm.	2x2 cm., yellow, slimy appearance.	2x2 cm., yellow, slimy.	2.5x2.5 cm., yellow, slimy.	....	....	....	6.5x6.5 cm., pink, appearing in concentric rings, fluffy on edge and middle.
In dark, humidity 98 per cent, temperature 25 to 27° C.	....	....	....	....	Check started.	5.5x5.5 cm., extremely fluffy and white.	8.5 x 8.5 cm., fluffy, pink in middle.	9.5x9.5 cm., fluffy, pink in middle.
In dark, temperature 45° C., humidity 5 to 50 per cent.	No growth.	No growth.	No growth.	No growth.	Removed to temperature 22° C.	No growth.	No growth.	No growth.
In dark, temperature 45° C., humidity 100 per cent.	No growth.	No growth.	No growth.	No growth.	Removed to temperature 22° C.	No growth.	No growth.	No growth.

TABLE 7.—*Influence of lactic acid.*

	February 12	February 19	February 26	April 3	April 4	April 8
Agar lactic acid.	Culture started.	1x1 cm., yellow, slimy.	1 5 x 1.5 c m., yellow, slimy	4x4 cm., exceedingly pink.	6x6 cm., very pink.	9.5x9.5 c m., very pink.

TABLE 8.—*Influence of low temperature.*

Temperature	April 1	April 27	April 28	May 1	May 8
1° C	Culture started.	Removed to temperature 3.3° C. No growth.	Slight growth.	Removed to temperature 22° C.	Good growth.
−3.9° C	Culture started.	Removed to temperature 3.3° C. No growth.	No growth.	Removed to temperature 22° C.	Good growth.
−22° C	Culture started.	Removed to temperature 3.3° C. No growth.	No growth.	Removed to temperature 22° C.	9.5 x 9.5 c m., pink and fluffy.

HUMIDITY.

The fungus grows best under moist conditions and it is apparent that in most cases the supply of moisture is the determining factor for infection.

COLOR.

The color studies were carried on with cultures grown on glucose agar and on potato plugs. In general, the color produced on potato plugs is much more constant than that produced on agar. The general appearance of a colony on agar may show great variation, at times on whole plates and at times only in isolated parts of the same plate. This is undoubtedly due to variation in the condition of the media, to moisture variation, and the like.

The cultures were grown in diffuse light, in the dark, at high and low temperatures, and in analyzed light. The cultures were on agar plates, on potato plugs, and on beef broth. Flask cultures on one per cent glucose and on synthetic media, in tap water and in distilled water were grown in the light and in the dark. Tables 6, 7 and 8 give in detail the observed colors which were noted on a series of cultures. Each series was run in triplicate.

The general color of the fungus when two to three weeks old is a pale pink, sometimes grading over to a flesh pink, Repertoire de Coleurs, page 135, No. 3, and 136, No. 1 (Pl. XXII). In the dark the cultures are more of a flesh pink color than pale pink. Whether the blue or red rays are shut out seems to be immaterial. In fact, variation between plates grown under the same condition may be greater than that between plates grown under different conditions. This does not hold for all species of *Fusarium* by any means, as shown by the *Fusarium* which we have found on Colorado potatoes. In the light, this fungus assumes a pink color; in the dark, a white, soon followed by a deep blue.

The plates placed in bright light so that the sun struck them during a part of the day, and so that the temperature rose to 30° to 40° C., showed the most intense color, but a slow growth. Here the color very often went over to the salmon tint, page 72 of the Repertoire, especially on the underside of the culture.

The question whether the colony will appear flesh-pink or pale-pink is largely a matter of secondary germination of the conidia. If these germinate on the original mat and the nutrients become exhausted before the second set of hyphae produce conidia, the mycelium color will tone the conidial color down to a pale pink. Conidia are produced more slowly in such cultures and the mycelial growth predominates. The growth here is rapid and the media are not exhausted completely as the fungus advances; consequently a secondary luxuriant growth takes place over the first layer. In bright light the growth is slower, more conidia are formed, and the mycelium uses up the food completely; consequently less secondary germination takes place and therefore the original pink color is not obscured. The catalytic effect of the sun's rays may have an influence fostering a more complete respiration of the media as the fungus grows along.

The cultures in flasks on liquid media gave contradictory results. The fungus when grown in distilled water and when grown in dark and in light develops a thin mycelium which shows a lilac mauve color, Repertoire, p. 196, No. 1. When grown in tap water the fungus grows very sparingly and develops no color at all. On 1 per cent glucose in light the fungus develops a color, Repertoire, p. 135, No. 3, when two or three weeks old and no surface growth occurs and no conidia are formed. In the dark the growth is very stunted and the color is white. Microscopically no difference, excepting that the fungus grown in the dark showed a very knotted appearance, is apparent. When grown on culture media in the light a very luxuriant growth of white mycelium takes place and no color is developed until the fungus reaches the surface and begins to form a mat of plectenchyma which soon becomes covered with innumerable new conidia. At no time does there develop any color in the mycelium in the medium.

When grown in the natural habitat, the potato away from light, the fungus is white, but as soon as exposed to light a distinct color develops. In the former case slight conidial formation is the rule, while in the latter great numbers of conidia are formed.

When grown on stems considerable variation in color appeared. When grown on young stems of a tuber grown under irrigation a rich pink color is developed but when grown on stems of a dry land variety the white color predominates. This may in age turn to an ochre tint.

Microscopically no difference can be seen. The cell sap is always of the lilac mauve color in all cultures, both in mycelium and in the spores. By putting the mycelium which has been grown in distilled water into strong mineral acid a red color often sets in.

The cell sap is always blue. When the growth is weak and no color is developed in the plasma and wall the cell sap color is visible in the mat. If conditions are not favorable for growth, changes in the plasma and walls obscure the cell sap color so that the mycelium is white. Macroscopically the spores are always pink. This color must be located in the plasma or wall and since the nature of the medium determines whether conidia will be formed or not it will also determine whether a pink color will appear or not. The light has an effect in so far as it catalytically influences the medium or in so far as it stunts the growth of the mycelium, causing it to go over into conidial formation. It might do this either by increasing the respiratory activities in the fungus or by inhibiting them.

In the 1 per cent sugar solution in light, the medium must be of such a nature as to produce color and not to cause conidial formation. On beef bouillon (+10) a slight aerial growth took place, few conidia were formed, and a very faint pink color resulted, so faint that it was scarcely visible.

Color therefore is constant as long as the organism is grown under ordinary constant conditions. The substratum and other environmental factors, especially light, can influence it slightly, however. The color is always in the pink category, and no complete changes from red to blue or to yellow, as we have found in the *Fusarium* from Colorado, are obtained in *Fusarium tuberivorum*. It is apparent that the nature of the medium and light has something to do with development of color in this organism. Which of these is the determining factor we have not been able to ascertain.

If a suspension of old spores is made in water, or when the fungus is grown on liquid media for 6 or 8 weeks, the liquids take on an ochre color. This probably is due to an oil which completely fills the conidia when they are old.

CONIDIOPHORES.

In *Fusarium orthoceras* the conidophore is generally only a sterigma-like branch arising laterally from a hypha and cutting off conidia from its end. Sometimes a conidiophore with a tri-sterigmate structure is found. Ordinarily as it is found on potato and as it grows on agar and on potato plugs, *Fusarium tuberivorum* shows the same structure of conidiophores that *Fusarium orthoceras* does (Pl. XXVI, fig. 1). In the cold, however, the tri-sterigmate conidiophore appears. On stems and on raw potato plates when quite dry, we find compound conidiophores in which each sterigma-like branch of the first order can branch into three others and thus three or four tiers are formed, presenting a complex compact mass resembling the structure of the conidiophores of *Fusarium rubiginosum* (Pl. XXVI, figs. 2 and 3).

CHLAMYDOSPORES.

In these cultures chlamydospores, which may be borne terminally or intercalarally, have appeared. Most of these are round and smooth and heavily stored with oil. On beef-bouillon agar and in distilled water the mycelium and spores can be made to fragment into oidia. Each of these cells is quite thick walled, hyaline, full of oil, and capable of germination. Their size generally is 6-12 x 8-12 mu (Pl. XXVII, figs. 1 and 3).

The writers have found single cells and compound cells which are thick walled, ochre colored, and spiny, only rarely in water and in potato tubes. On a raw potato plate numerous chlamydospores appeared only once in a series of several hundred cultures. The fungus has been grown by others for a year or so in this laboratory and not once did chlamydospores appear during that time (Pl. XXVII, figs. 2, 3, 4, 5, 6, 7, and 8).

It is apparent that with this character we have a variable thing, so variable that under proper conditions the whole fungus can be made to go over into the oidia form and look like a *Cladosporium*. Dry air and low food supply seem to favor the development of these oidia and chlamydospores. The size of the chlamydospore generally is 8-12 x 10-12 mu.

SPORE MEASUREMENT.

The measurements of spores taken from various cultures in all stages of development show a surprising uniformity, the only exception appearing in those spores which were grown at low temperatures, they being a trifle wider than the ordinary spores.

On agar the following are the averages:

	Width.	Length.
0-septate	3.2 mu.	8 to 11 mu.
1-septate	3.2 to 5 mu.	11 to 20 mu.
2-septate	3.2 to 5 mu.	12 to 22 mu.
3-septate	4 to 5 mu.	17 to 22 mu.

On potato plugs in the light.

	Width.	Length.
0-septate	3 to 5 mu.	11 to 16 mu.
1-septate	3 to 5 mu.	10 to 18 mu.
2-septate	3 to 5 mu.	16 to 22 mu.

On potato plugs in the dark.

	Width.	Length.
0-septate	2.4 to 3.3 mu.	8 to 13 mu.
1-septate	3.2 to 5 mu.	10 to 20 mu.
2-septate	3.2 to 5 mu.	18 to 25 mu.
3-septate	5 mu.	22 to 25 mu.

The greatest spore length noted was 40 mu. This spore was 3 mu wide. The greatest width noted was 5.8 mu. The great majority of all spores measured is 5 x 17-20 mu.

In measuring spores the diameter of the septum was measured, which gives a reliable basis for width determination. In measuring the length, the length of the segment between the two extremities was measured rather than the length of the arc of the curvature of the spore.

The spores of *Fusarium solani*, as to length, compare most closely to those of *Fusarium tuberivorum*, but they are longer than we find the spores of the latter to be. They also are a trifle wider than the spores of *Fusarium tuberivorum*. The only other species which could be confused with *Fusarium tuberivorum* is *Fusarium orthoceras*. The spores in this species are too narrow, however. Neither *Fusarium solani* nor *Fusarium orthoceras* gives the percentages which would make it possible for any one to confuse the three species. The percentages of *Fusarium solani* according to Appel and Wollenweber are:

1-septate	8 to 0 per cent.
2-septate	14 to 0 per cent.
3-septate	67 to 90 per cent.
4-septate	16 to 0 per cent.
5-septate	6 to 0 per cent.

For *Fusarium orthoceras.*

0-septate	92 per cent.
1-septate	5 per cent.
2-septate	Few.
3-septate	3 per cent.
4-5-septate	Few.

For *Fusarium tuberivorum,* culture 150 days old.

0-septate	Few.
1-septate	98 per cent.
2+-septate	Very few.

SUMMARY.

We have in *Fusarium tuberivorum* an interesting organism, both from a morphological and from a physiological point of view. If we consider all species of *Fusarium* as belonging together, we can look upon *Fusarium orthoceras* either as the farthest away from its ascomycete ally, if there is any, or as nearest to it. If the contentions that some of the species of *Fusarium* have been connected with certain *Nectria* will hold, or that *Neocosmospora* is closely related, it is apparent that such related species of *Fusarium* are characterized by the presence of several-septate curved spores. Then such a form as *Fusarium orthoceras* would have to be considered the most remote relative. It is possible of course that *Fusarium* is such a Babel as the genus *Gloeosporium* and that it is a sort of rendezvous for the ends of several ascomycete forms. If the latter is the case it will be almost useless to try to combine the *Fusarium* species into a coherent assemblage. On the other hand, if they are related it will be necessary to link only one of these species to an ascomycete form to give all of them their proper place. It is a perplexing state of affairs, however, that the Ascomycetes to which the *Fusarium* species have often been referred are themselves in about as orderly a state as the *Fusarium* spcies are.

No matter whether we adopt one or the other view, it seems quite safe to say that *Fusarium tuberivorum* shows nicely the transitions by which such forms as *Fusarium orthoceras* and *Fusarium solani* or *Fusarium theobromae* can be connected. Especially is this true since the characters which appear under normal conditions in this fungus can be varied considerably by changing the environment.

Fusarium orthoceras normally shows a preponderating number of non-septate conidia and only a few 3-septate conidia. The spores are not curved and show no decided differentiation of apical and basal cells. *Fusarium solani* ordinarily shows the curved 3-septate conidium and only rarely the non-septate form, altho this can be changed by putting the fungus under hard conditions. *Fusarium solani* shows a fair differentiation of its basal and apical spore cells.

Fusarium tuberivorum shows all the spore forms that have been noted in species of *Fusarium.* Normally, however, a preponderating number of 1-septate and only a few 3-septate ones occur. The spores show no decided differentiation in their basal and apical cells. Under proper conditions, only non-septate spores appear, and these show no differentiation of their ends. Under other conditions the number of 3-septate spores can be greatly increased and the most typical end differentiation realized.

Fusarium orthoceras shows the simple sort of conidiophore and only at times a simple tri-sterigmate one. *Fusarium solani* ordinarily shows a compound conidiophore and rarely the simple types. *Fusarium tuberivorum* usually shows the *orthoceras* type but can be made to develop the most complex sort of a conidiophore built on the tri-sterigmate plan.

Fusarium orthoceras shows typical intercalary and terminal chlamydospores; some species of *Fusarium* have neither. Ordinarily *Fusarium tuberivorum* has none but under extreme conditions it can be forced to develop both the terminal and the intercalary kind. As far as size is concerned the spores of *Fusarium tuberivorum* stand with the smallest of the species of *Fusarium,* being a little wider than those of *Fusarium orthoceras* and not so long, and a little longer than those of *Fusarium solani* and not so wide.

FUSARIUM TUBERIVORUM SP. N. WILCOX AND LINK.

The following diagnosis is based upon the characters displayed by this fungus when grown on potato plugs in diffuse light at 22° to 27° C.

Conidia not in layers *(Pionnotes* on glucose agar, sporodochia occasionally on old dry tubers of *Solanum tuberosum).* Normal mature conidium fusiform to slightly clavate, slightly bent, no differentiation of terminal cells; 1-septate, generally 3-5x7-20 mu. Few 0-, 2-, 3-septate spores, 2.4-3.3x7-13 mu; limits 4-7 septate, 5.2x40 mu.

Conidial color pale pink, Repertoire des Couleurs des Chrysanthemists, p. 135, No. 3, turning to ochre when very old. Conidiophores simple, sterigma-like, short, occasionally branching in a tri-sterigmate manner.

Subaerial mycelium white, appearing flesh pink, Repertoire, p. 136, No. 1, when mixed with conidia. Chlamydospores appear rarely in either terminal or intercalary position. Size 6-12 x 8-12 mu.

Occurrence: On tubers of *Solanum tuberosum,* causing a dry rot, and upon dry potato stems.

ETIOLOGY.

TUBER INFECTIONS.

A very large number of inoculation experiments have now been made so that the connection of *Fusarium tuberivorum* with this Nebraska tuber rot is fully established.

The first inoculations were made in 1908 on tubers grown in eastern Nebraska. Puncture inoculations into these tubers gave no evidence of rotting, due no doubt to the comparatively great resistance of these tubers to invasion by this fungus.

TABLE 9.—*Inoculations of western Nebraska tubers made during the winter of 1908-1909.*

No. of tubers	No. of inoculations per tuber	Method of inoculating	Humidity	No. of successful inoculations
12	4	Puncture	60	48
10	4	Puncture	Over H_2SO_4	40
8	4	Puncture	Saturated air	16
3	4	Smear	60	Tubers showed a soft bacterial rot.
Check 2	4	Puncture with sterile needle	60	None

The tubers kept in a desiccator over sulfuric acid and those kept at the humidity of the laboratory (averaging about 60 per cent during the experiment) gave the largest number of successful inoculations and the greatest amount of rotting. These preliminary experiments clearly established the causal relation of this specific fungus to the dry rot of these tubers.

Extensive inoculation experiments were conducted during the spring of 1910 with several bushels of large healthy Early Ohio and White Ohio tubers grown in Box Butte County. The following types of inoculation were employed in this work:

1. Contact with infected tubers.
2. Punctures.
    A. At the "eye."
    B. At some other point on the surface of the tuber.
3. By removal of the "skin" of the tuber.
4. Surface infection, with and without media.
    A. At the stem end of the tuber.
    B. At a lenticel.

CONTACT INOCULATION.

On March 26, 1910, a severely rotted Early Ohio tuber was placed in contact with healthy tubers. Similar experiments were made with rotted tubers of the White Ohio potato. It should be stated that, in both cases, the healthy tubers employed had an unbroken surface. On April 26 the tubers were carefully examined and no sign of infection was found in any of the surrounding healthy tubers of either variety.

EYE PUNCTURES OF EARLY OHIO.

TABLE 10.—*A summary of the results of 102 "eye" punctures, in all of which some medium was applied with the fungus. The greatest amount of rot appeared here on tubers kept at the lower temperature and in the highest relative humidity.*

No. of inoculations	No. of successful inoculations	Extent of rot	Temperature	Humidity
18	18	Slight	24 to 27° C.	Saturated air
18	18	Slight	24 to 27° C.	Over $CaCl_2$
18	18	1 cm. deep......	8 to 10° C.	Over $CaCl_2$
18	18	1.5 cm. deep	8 to 10° C.	Saturated air
30	30	Slight to ⅔ of the tuber...	8 to 10° C.	Saturated air

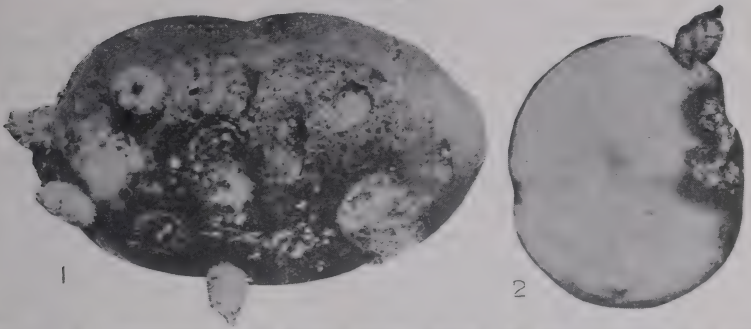
SURFACE PUNCTURES OF EARLY OHIO.

TABLE 11.—*Results of 132 surface puncture inoculations, in all of which medium was applied.*

No. of inoculations	No. of successful inoculations	Extent of rot	Temperature	Humidity
18	18	Very slight	25 to 27° C....	Saturated air
18	18	Slight...	25 to 27° C....	Over $CaCl_2$
18	18	1 cm. deep......	8 to 10° C....	Over $CaCl_2$
78	78	Prominent in 7 days; in 4 weeks entire tuber rotted	8 to 10° C....	Saturated air

It will be noted that the rot developed on tubers kept at high or low temperatures and at high or low relative humidity. A greater amount of rotting occurred at the lower temperature with either high or low humidity.

SURFACE INOCULATIONS OF EARLY OHIO TUBERS AFTER REMOVAL OF THE SKIN.

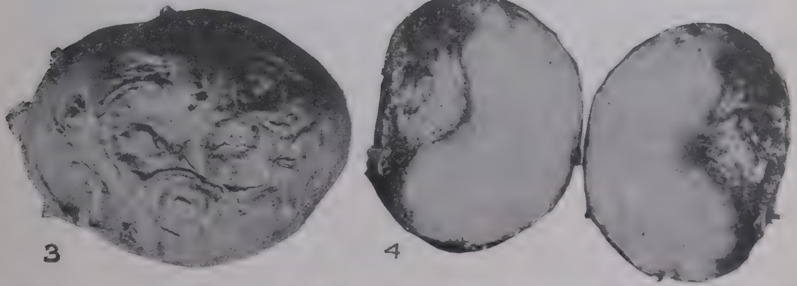


Figs. 1, 2. Inoculation of Early Ohio tubers by removal of the skin. Photographed five weeks after inoculation. Kept in a moist chamber with a small dish of water; the first week at 8° to 10° C. and then at laboratory temperature. Medium applied with the fungus.

TABLE 12.—*Results of inoculation, with and without media, on the surface after the removal of the skin of the tuber.*

No. of inoculations	No. of successful inoculations	Extent of rot	Medium	Temperature	Humidity
18	0	None.....	Yes	25 to 27° C.	Saturated air
18	0	None......	Yes	25 to 27° C.	Over $CaCl_2$
18	0	None.....	Yes	8 to 10° C.	Over $CaCl_2$
18	11	1 cm. deep.	Yes	8 to 10° C.	Saturated air
30	18	Prominent; 2 cm. deep	Yes ...	8 to 10° C.	Saturated air
30	4	Moderate..	No....	8 to 10° C.	Saturated air

It is evident in this case that the greatest amount of rotting occurred at high humidity.



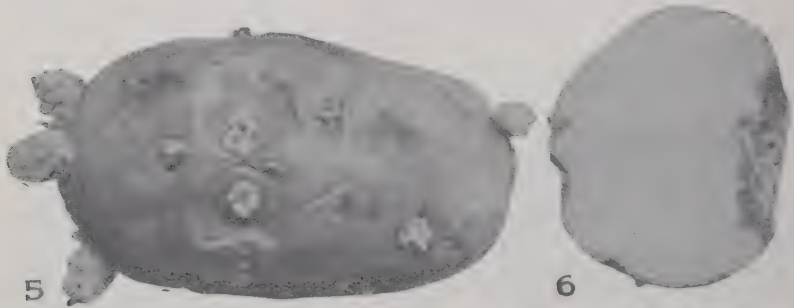
Figs. 3, 4. Inoculation of Early Ohio tubers by removal of the skin. Photographed four weeks after inoculation. Kept over $CaCl_2$; the first week at 8° to 10° C. and then at laboratory temperature. With medium.

SMEAR INOCULATIONS ON EYE, LENTICEL, OR SURFACE OF EARLY OHIO.

Inoculations, with or without medium, made directly upon the eye, lenticel, or other surface of the tuber gave no infection in any case. Of course in all such cases the surface was unbroken.

TABLE 13.—*Results of a large number of inoculations made March 21, 1910, on Early Ohio tubers which were subsequently kept in an atmosphere having a very high humidity.*

Part inoculated	No. of tubers inoculated	No. of inoculations per tuber	Temperature	No. of successful inoculations	Extent of rot
Eye puncture ..	5	6	8 to 10° C.	30	
Eye surface....	5	6	8 to 10° C.	0	
Eye surface....	5	6	8 to 10° C.	0	
Lenticel surface	5	6	8 to 10° C.	0	
Lenticel surface	5	6	8 to 10° C.	0	
Other than lenticel surface..	5	6	8 to 10° C.	0	
Other than lenticel surface..	5	6	8 to 10° C.	0	
Epidermis removed. ...	5	6	8 to 10° C.	18	Prominent; $\frac{3}{4}$ in. in diameter
Epidermis removed.......	5	6	8 to 10° C.	4	
Surface puncture	10	6	8 to 10° C.	60	



Figs. 5, 6. Inoculation of Early Ohio tubers by removal of the skin. Photographed four weeks after inoculation. Kept in a moist chamber containing a small dish of water; the first week at 8° to 10° C. and then at laboratory temperature. No medium employed.

The last three sets in the above summary were on March 28 removed to moist chambers with $CaCl_2$ and kept at the temperature of the laboratory.

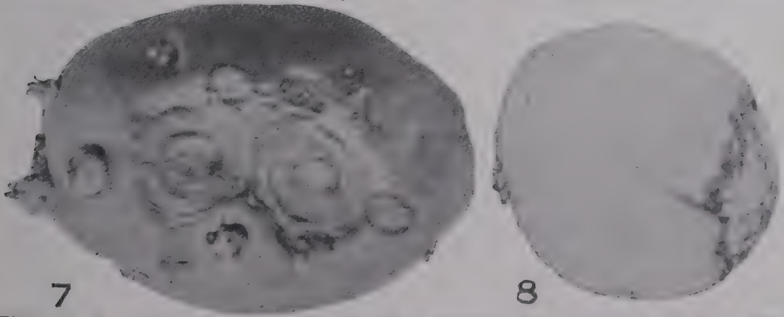
TABLE 14.—*Summary of inoculations made on March 28, 1910, on Early Ohio tubers subsequently kept in an atmosphere of very high humidity. The tubers were examined on April 27.*

Part inoculated	No. of tubers inoculated	No. of inoculations per tuber	Temperature	Extent of rot
Eye puncture	3	6	25 to 27° C.	No rot
Surface puncture	3	6	25 to 27° C.	No rot
Epidermis removed	3	6	25 to 27° C.	No rot

TABLE 15.—*Inoculations of Early Ohio tubers made March 29, 1910.*

	Method of inoculation	No. of tubers inoculated	No. of inoculations per tuber	Temperature	No. of successful inoculations	Extentf op rot
Over $CaCl_2$	Eye puncture	3	6	8 to 10° C.	18	1 cm. deep
	Puncture	3	6	8 to 10° C.	18	1 cm. deep
	Epidermis removed	3	6	8 to 10° C.	0	
Saturated air	Eye puncture	3	6	8 to 10° C.	18	1.5 cm. dee
	Puncture	3	6	8 to 10° C.	18	1 cm. deep
	Epidermis removed	3	6	8 to 10° C.	11	1 cm. deep
Over $CaCl_2$	Eye puncture	3	6	24 to 27° C.	18	Slight
	Puncture	3	6	24 to 27° C.	18	Slight
	Epidermis removed	3	6	24 to 27° C.	0	

It is probable that the amount of $CaCl_2$ employed was not sufficient to give extreme dryness within these chambers.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Figs. 7, 8. Inoculation of Early Ohio tubers by removal of the skin. Photographed four weeks after inoculation. Kept over $CaCl_2$; the first week at 8° to 10° C. and then at laboratory temperature. No medium employed.

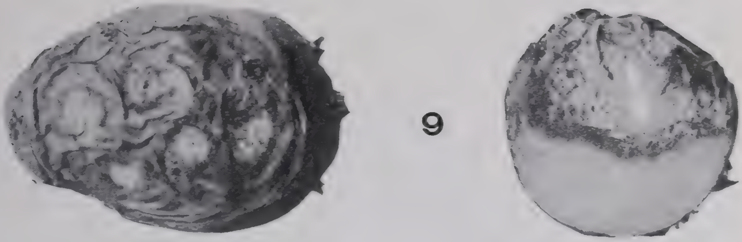
Table 16.—*Inoculation experiments with the White Ohio tubers by placing the inoculum on the surface after removing the skin of the tuber.*

No. of inoculations	No. of successful inoculations	Medium used	Temperature	Humidity
30	0	Yes	25 to 27° C......	Saturated air
30	0	No.......	25 to 27° C ...	Saturated air
6	0	Yes	25 to 27° C	Over H_2SO_4
6	0	Yes	25 to 27° C......	Saturated air
30	18	Yes	8 to 10° C......	Saturated air
30	4	No	8 to 10° C......	Saturated air

Here again it is evident that the use of medium with the fungus gives a greater number of successful inoculations, particularly at lower temperatures and higher relative humidity.

Table 17.—*Unsuccessful inoculation experiments with White Ohio tubers in cases in which the fungus was applied, with and without medium, on the unbroken surface at the places indicated.*

Method of inoculation	No. of inoculations	No. of successful inoculations	Medium used	Temperature	Humidity
Eye surface.....	30	0	Yes ...	25 to 27° C.	Saturated air
Eye surface.....	30	0	No....	25 to 27° C.	Saturated air
Eye surface.....	30	0	Yes ...	8 to 10° C.	Saturated air
Eye surface.....	30	0	No ...	8 to 10° C.	Saturated air
Lenticel surface..	30	0	Yes ...	25 to 27° C.	Saturated air
Lenticel surface..	30	0	No....	25 to 27° C.	Saturated air
Lenticel surface..	60	0	Yes ...	8 to 10° C.	Saturated air
Lenticel surface..	30	0	No...	8 to 10° C.	Saturated air
Stem-end surface	5	0	Yes ..	25 to 27° C.	Saturated air
Stem-end surface	5	0	No....	25 to 27° C.	Saturated air
Stem-end surface	5	0	Yes ...	8 to 10° C.	Saturated air



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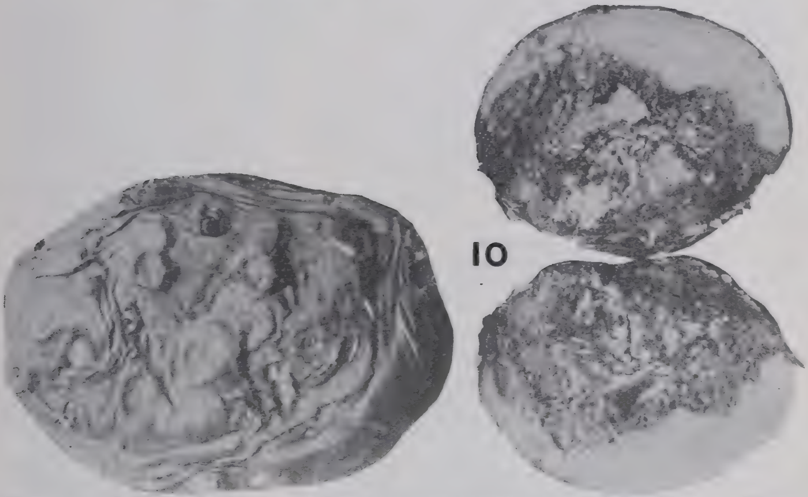

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Figs. 9, 10. Inoculation of Early Ohio tubers thru punctures. Photographed four weeks after inoculation. Kept over $CaCl_2$; the first week at 8° to 10° C. and then at laboratory temperature.

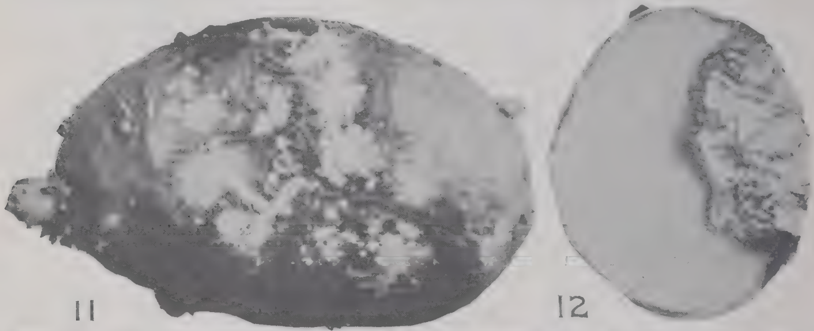
TABLE 18.—*Puncture inoculations made on White Ohio tubers, in all cases medium being applied.*

Method of inoculation	No of inoculations	No. of infections	Extent of rot	Temperature	Humidity
Surface puncture	30	4	Slight	25 to 27° C.	Saturated air
Surface puncture	54	51	3 cm. deep	25 to 27 C	Over $CaCl_2$
Surface puncture	6	4	Very slight	25 to 27 C.	Over H_2SO_4
Surface puncture	30	30	1 cm. deep	8 to 10 C.	Saturated air
Eye puncture	30	0	....	25 to 27 C.	Saturated air
Eye puncture	3	0	....	25 to 27° C.	Over H_2SO_4
Eye puncture	3	0	....	25 to 27° C.	Over H_2SO_4
Eye puncture	30	30	1 to 3 cm. deep	8 to 10 C.	Saturated air

The White Ohio tubers did not prove as susceptible as the Early Ohio tho the rotting was related in the same manner to the factors mentioned in the summaries. At the lower temperatures and with high relative humidity successful inoculations were secured in each case.

TABLE 19.—*Inoculation experiments made with the White Ohio tubers. In all these cases the tubers were subsequently kept in a saturated air at 25° to 27°C. The final examination was made on April 18 with the results indicated.*

Method of inoculation	No. of tubers inoculated	No. of inoculations per tuber	No. of successful inoculations
Eye puncture	5	6	0
Eye surface	10	6	0
Stem-end surface	10	6	0
Lenticel surface	10	6	0
Surface puncture	5	6	4
Epidermis removed	10	6	0



Figs. 11, 12. Inoculation of Early Ohio tubers thru punctures. Photographed four weeks after inoculation. Kept in a chamber with a small dish of water; the first week at 8° to 10° C. and then at laboratory temperature.

TABLE 20.—*Inoculation experiments with White Ohio tubers are reported in the following table. Examination made March 18, seven days after inoculation.*

Method of inoculation	No. of tubers inoculated	No. of inoculations per tuber	Humidity	Temperature	Extent of rot
Surface puncture	1	6	Over H_2SO_4	25 to 27° C.	None
Eye puncture	1	3	Over H_2SO_4	25 to 27° C.	None
Epidermis removed	1	6	Over H_2SO_4	25 to 27° C.	None
Surface	1	6	Over H_2SO_4	25 to 27° C.	None
Surface puncture	1	6	Moist chamber	25 to 27° C.	Slight
Eye puncture	1	3	Moist chamber	25 to 27° C.	None
Epidermis removed	1	6	Moist chamber	25 to 27° C.	None

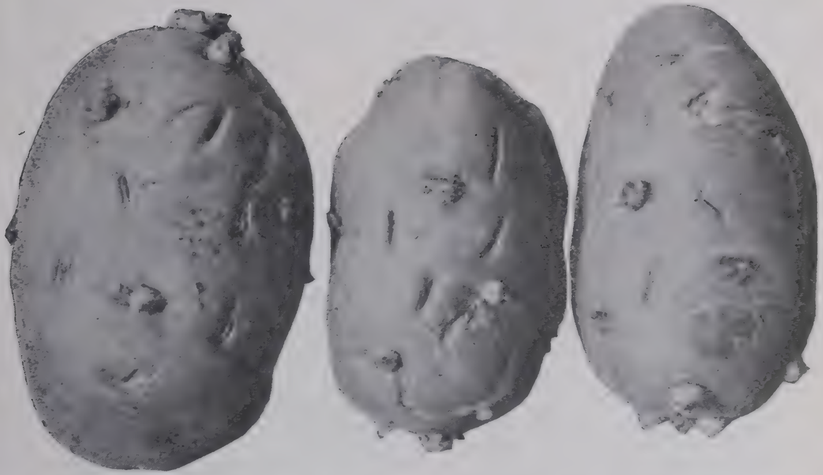


Fig. 13. Inoculation of White Ohio tubers thru punctures. Photographed five weeks after inoculation. Kept in a moist chamber at 25° to 27° C. Only 4 successful infections out of 30 were secured,—the punctures as a rule simply dried out.

TABLE 21.—*Inoculations made March 25 or 28 and examination made on April 25. The tubers were kept at 8° to 10° C. in moist chambers.*

Method of inoculation	No. of tubers inoculated	No. of inoculations per tuber	No. of successful inoculations	Medium used	Extent of rot
Eye puncture	5	6	30	....	1 to 3 cm. deep
Eye surface	5	6	0	Yes	
Eye surface	5	6	0	No	
Stem end	5	1	1		
Lenticel	5	6	0	Yes	
Lenticel	5	6	0	No	
Puncture	5	6	30		
Epidermis removed	5	6	18	Yes	
Epidermis removed	5	6	4	No	
Surface not at lenticel	5	6	0	Yes	
Surface not at lenticel	5	6	0	No	

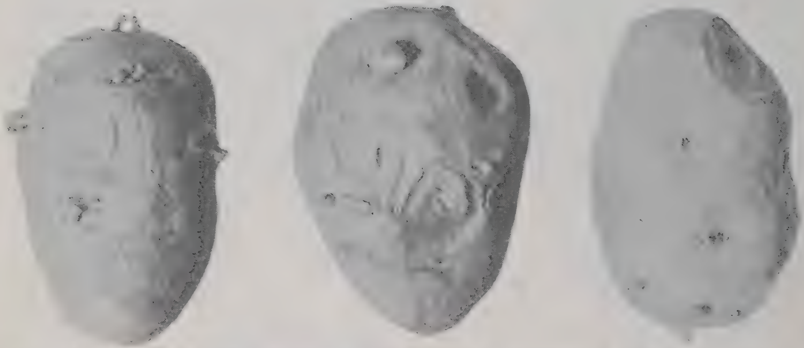


Fig. 14. Comparative extent of the rotting following different types of inoculation. Inoculated March 29.

INOCULATION OF "NEW" TUBERS OF EARLY OHIO.

New potato tubers were obtained at Alliance and inoculated September 3, 1909.

TABLE 22.—*Inoculation of tubers subsequently covered with moist absorbent cotton and left exposed to the ordinary room conditions, the air being usually very dry and warm. The examination was made six weeks after inoculation.*

Method of inoculation	No. of tubers inoculated	No. of inoculations per tuber	No. of successful inoculations	Extent of rot
Epidermis removed	7	2	14	One-half of tuber rotted
Surface puncture..	13	4	52	One-half of tuber rotted
Thru scab spots...	8	4	0	
Smear	8	4	0	

It will be noted that the simple removal of the skin supplied as suitable a means of entrance for the fungus as did punctures. No infection occurred thru the scab spots nor thru the uninjured surface. The rot developed more slowly than it does in more matured tubers.

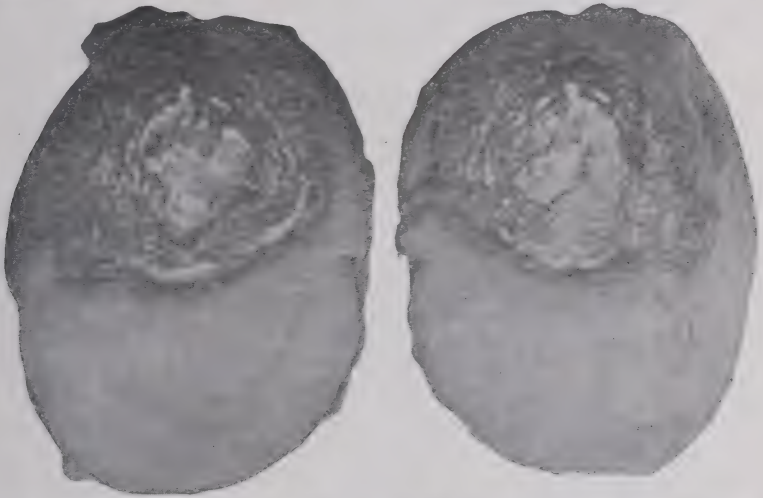


Fig 15. Rotted tubers cut open to show the frequent occurrence of a concentric arrangement of the rotted areas.

NATURAL FIELD INOCULATIONS.

During 1909, extensive experiments were conducted at Alliance to test the effect of planting rotted seed pieces in the hills. This was designed to throw light upon the question of natural infection under field conditions and the value, if any, of Bordeaux spraying. For this experiment, the following varieties were used:

(1) Acme.
(2) Rural New Yorker.
(3) Early Ohio.
(4) Red River Valley Ohio.

The Rural New Yorker potatoes employed were purchased in the Lincoln market; the Red River Valley Early Ohio potatoes were purchased in the Alliance market; the Acme potatoes had been grown by W. A. Springer of Alliance, while the Early Ohio potatoes were grown by Wm. Lorance of Alliance.

The arrangement of the rows and the nature of the treatment each received is shown in the following table:

Potato experiments on the farm of Wm. Lorance near Alliance.

Plot	Row	Variety	
A	1	Acme	Without any rot pieces in the hills and not sprayed.
	2	Rural New Yorker—Untreated	
	3	Lorance's Early Ohio	
	4	Red River Valley Early Ohio	
	5	Acme	
	6	Rural New Yorker—Untreated	
	7	Lorance's Early Ohio	
	8	Red River Valley Early Ohio	
	9	Rural New Yorker—Untreated	
	10	Rural New Yorker—Treated with formalin.	
B	1	Acme	With "end rot" pieces in the hills and sprayed.
	2	Rural New Yorker—Untreated	
	3	Lorance's Early Ohio	
	4	Red River Valley Early Ohio	
	5	Acme	
	6	Rural New Yorker Untreated	
	7	Lorance's Early Ohio	
	8	Red River Valley Early Ohio	
	9	Rural New Yorker—Untreated	
	10	Rural New Yorker—Treated with formalin.	
C	1	Acme	With "end rot" pieces in the hills but not sprayed.
	2	Rural New Yorker—Untreated	
	3	Lorance's Early Ohio	
	4	Red River Valley Early Ohio	
	5	Acme	
	6	Rural New Yorker—Untreated	
	7	Lorance's Early Ohio	
	8	Red River Valley Early Ohio	
	9	Rural New Yorker—Untreated	
	10	Rural New Yorker—Treated with formalin.	
D	1	Acme	With "dry rot" pieces in the hills and sprayed.
	2	Rural New Yorker -Untreated	
	3	Lorance's Early Ohio	
	4	Red River Valley Early Ohio	
	5	Acme	
	6	Rural New Yorker—Untreated	
	7	Lorance's Early Ohio	
	8	Red River Valley Early Ohio	
	9	Rural New Yorker—Untreated	
	10	Rural New Yorker—Treated with formalin.	
E	1	Acme	With "dry rot" pieces in the hills but not sprayed.
	2	Rural New Yorker—Untreated	
	3	Lorance's Early Ohio	
	4	Red River Valley Early Ohio	
	5	Acme	
	6	Rural New Yorker—Untreated	
	7	Lorance's Early Ohio	
	8	Red River Valley Early Ohio	
	9	Rural New Yorker—Untreated	
	10	Rural New Yorker—Treated with formalin	

Almost one thousand plants were thus exposed to exceedingly favorable conditions for dry-rot infection to occur. Every single tuber was examined at harvest time and no evidence of dry rot was discovered.

Table 23.—*Data of field experiments conducted at Alliance during the summer of 1909.*

Plot	A										
Row	1	2	3	4	5	6	7	8	9	10	Per cent
Number of marketable tubers	50	91	175	122	163	120	189	132	117	61	
Number with stem-end rot	26	62	109	72	80	80	89	132	76	43	
Percentage of marketable tubers	...	...	...	...	...	...	...	...	...	...	70
Number of unmarketable tubers	34	74	39	38	15	81	39	30	82	116	
Number with stem-end rot	11	39	39	12	4	36	15	7	44	75	
Total percentage with stem-end rot	...	...	...	...	...	...	...	...	...	...	60

Table 23.—*Data of field experiments conducted at Alliance during the summer of 1909—Continued.*

Plot	B										
Row	1	2	3	4	5	6	7	8	9	10	Per cent
Number of marketable tubers	204	90	140	174	237	134	126	147	123	154	
Number with stem-end rot	145	66	67	95	146	62	51	63	54	83	
Percentage of marketable tubers		...	...		...	...	...	...	...	...	73
Number of unmarketable tubers	19	60	15	...	33	35	63	39	85	53	
Number with stem-end rot	9	45	...	...	7	19	22	17	34	20	
Total percentage with stem-end rot	...	...	...	...	...	...	...	...	...	...	51

Table 23.—*Data of field experiments conducted at Alliance during the summer of 1909—Continued.*

Plot	C										
Row	1	2	3	4	5	6	7	8	9	10	Per cent
Number of marketable tubers	177	131	137	135	120	77	125	83	132	98	
Number with stem-end rot	96	76	48	63	28	46	49	37	75	31	
Percentage of marketable tubers											67
Number of unmarketable tubers	40	160	27	38	33	99	32	30	72	41	
Number with stem-end rot	12	107	5	15	13	47	12	9	35	20	
Total percentage with stem-end rot											46

Table 23.—*Data of field experiments conducted at Alliance during the summer of 1909—Continued.*

Plot	D										
Row	1	2	3	4	5	6	7	8	9	10	Per cent
Number of marketable tubers	113	86	120	102	104	82	98	87	124	99	
Number with stem-end rot	64	37	42	60	59	24	46	31	83	56	
Percentage of marketable tubers											71
Number of unmarketable tubers	36	29	21	16	42	84	29	32	68	43	
Number with stem-end rot	12	15	7	8	15	38	9	11	27	22	
Total percentage with stem-end rot											47

TABLE 23.—*Data of field experiments conducted at Alliance during the summer of 1909—Concluded.*

Plot	E										
Row	1	2	3	4	5	6	7	8	9	10	Per cent
Number of marketable tubers	43	82	133	187	73	69	103	130	74	126	
Number with stem-end rot	39	61	75	103	35	35	56	71	45	53	
Percentage of marketable tubers											64
Number of unmarketable tubers	16	102	36	41	14	38	24	66	120	102	
Number with stem-end rot	7	74	16	24	2	12	12	23	55	24	
Total percentage with stem-end rot											52

The data in the above table are of considerable interest since they so clearly show that the dry rot here described cannot be communicated to the underground parts of the potato plant. In the hills in which a badly rotted piece of potato was placed at planting time, as many marketable tubers were produced as in the hills without any such treatment. In fact *no dry rot* appeared on any of these tubers at harvest time whether dry rot pieces were planted in the hill or not. The planting of tubers affected with stem end rot* with the seed piece in each hill of plots B and C apparently did not at all increase the percentage of tubers affected with stem end rot or bundle blackening. Previous treatment of the seed potatoes with formalin and subsequent spraying with Bordeaux mixture had no apparent effect upon the crop either as to the total yield or as to the percentage of marketable potatoes.

Moreover, during the seasons of 1909 and 1910 thoro search was made for dry rot on the new tubers. These observations covered ten fields containing a total of about five hundred acres. Not a single affected tuber was found during the summer. Plants and new tubers were secured from various fields during the summer of 1909 and a total of seven hundred and twenty isolations made from tubers and stems but the dry rot fungus was not secured. In one field, however, on August 26, dead potato stalks were found which were entirely rotted and crumbled when disturbed. From these stalks cultures of the fungus were obtained, together with bacteria. During the summer of 1910 in only one field were the plants found to be infected. The organism seems to exist merely as a saprophyte in the field and does not attack the tubers until they are harvested.

NATURAL INFECTION WITH DRY ROT.

Potatoes grown in western Nebraska were planted March 1, 1909, in the open bench of the greenhouse. These tubers were quite badly infected with dry rot, but to make certain, thoro infection of the soil, pieces of the rotted tissue were scattered thru the soil with the "seed" pieces. These plants made a good growth and remained green and healthy for twelve weeks. The new tubers were examined at frequent intervals but no sign of dry rot appeared. After the tops died, forty of the tubers, with the soil still clinging to them, were placed in moist chambers but no dry rot appeared on any of them.

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* The "stem-end" rot here referred to includes the symptoms of vascular discoloration described and illustrated by Smith and Swingle 1904 and assumed by them and many others to be caused by *Fusarium oxysporum* (p. 67). During the course of these investigations numerous isolations were made in various ways from a large number of tubers which showed clearly that, when present at all, the *Fusarium* hyphae were invading diseased tissues. It was found that in many cases saprophytic fungi and bacteria can invade this diseased tissue as readily and frequently as does *Fusarium.*

ARTIFICIAL INFECTION.

During the summer of 1909 at Alliance inoculations with *Fusarium tuberivorum* were made, in the field, into the growing plant and the newly forming tuber. The first inoculations were made July 29 when the plants were in prime condition. New tubers, three to five centimeters in diameter, were carefully separated out by themselves, wiped clean with cotton, inoculated, and then paper placed around them to prevent contamination. One tuber on each of ten plants was inoculated once. Four inoculations were also made into the stalks of these same plants below the soil level. The soil was carefully replaced over the tubers and around the plant in a manner comparable to the surrounding conditions. The plants were not injured in this way and growth was not retarded. Examinations were frequently made but no infection was found to take place.

In January, 1910, inoculation experiments were carried on under greenhouse conditions. Paraffined baskets were used which were large enough to hold about fifteen kilograms of soil. All paraffined baskets were washed with mercuric chloride and filled with sand which had been autoclaved for one-half hour at 115° C. Potato tubers which were treated with mercuric chloride were simply wiped off with cotton or allowed to dry after a wetting in the solution. The knife used in cutting was heated and cooled between the cutting of the different tubers. In two baskets the seed pieces were taken from healthy tubers and a pure culture of *Fusarium tuberivorum* placed upon the cut surface of each piece. Sixteen days after planting, the plants were examined. One seed piece was "crumbly" and rotted and the plant was small and worthless. Anoter seed piece was slightly infected but the plant produced was in fair condition of growth. Three other seed pieces were not at all infected and produced strong healthy plants. Twenty-three days after planting neither the new tubers nor the plants showed any infection but all the old seed pieces showed a slight rotting. After the plants had grown for two months in two other baskets they were inoculated just below soil level with *Fusarium tuberivorum*. No infection resulted.

During the winter of 1911-1912 inoculations of very young shoots were made in the laboratory. None of these were successful. These were made because an apparent infection had taken place in the laboratory in another experiment. Potato tubers had been sterilized with corrosive sublimate solution and then cut into slices and put into sterile petri dishes. Some of the fungus was inoculated into these sections in December just before the Christmas holidays. One of these sections was the bud end of the tuber and the fungus was placed near the terminal bud. These cultures were neglected for several weeks during the holidays and when the researches were again resumed it was found that one of the young shoots that had developed had been overrun by the *Fusarium,* and the death of the shoot was attributed to the fungus. Later on, a section of one of these slices was used in some inoculation experiments with plants which were covered with bell jars after the pieces had been placed in contact with the stem. The soil and pot had been sterilized, and much to our surprise a luxuriant growth of *Rhizoctonia* developed in a few days. This showed clearly that the washing of the tuber had not killed all of the organisms in or on the skin of the tuber and reopened the other observations, made on the other slices of the same potato, for further consideration. It is very possible that *Rhizoctonia* developed during the holidays and killed the shoot, which was subsequently invaded by *Fusarium.* Other experiments that have been performed with pure cultures and sterilized soil have all been negative in result and therefore this single instance of an apparent infection must be accepted with due reserve.

If this fungus is responsible for the wilt of potato vines at all, it must get into the young underground stems and roots. Manns reports successful inoculations by wounding roots in the presence of the fungus and by growing the potatoes in "sick soil," and says: "The disease came on much more definitely under the sick soil infection than it did where pure artificial cultures were used without incisions or root injury. The great difference between sick soil infection and that from pure cultures or even internal seed infection is that in the use of sick soil the roots are attacked at practically every point, while with pure cultures, or seed internally infected, the fungus attacks only in close proximity to the main root, while most of the secondary roots and the roots and the root hairs remain healthy."

Data from such experiments must, at the best, be very unreliable. "Sick soil," selected at random, may contain a multitude of fungi other than the particular fungus in question. The only reliable way of getting sick soil is to thoroly sterilize the soil and then inoculate it with pure cultures of the organism in question. *Rhizoctonia solani* is reported as an active damping off agent and it may have caused the attacks which are referred to above as occurring "at practically every point." The present authors' observations of the past summer tend to substantiate this view. The same objections must be raised against all experiments in which wounded plants are planted in non-sterile soil.

These experiments show quite conclusively that *Fusarium tuberivorum* cannot cause a wilt of potato vines by attacking live stems, subterranean or aerial. In spite of the fact that no successful inoculation experiments producing such a wilt with a *Fusarium* have ever been reported, the literature is full of references to such inoculations.

Most workers and reviewers have read inoculation experiments into Smith and Swingle's bulletin tho none are there reported. Most of the publications of the United States Department of Agriculture and the Experiment Stations dealing with the wilt of potatoes consider the causal connection of a *Fusarium* with a dry rot and wilt as established by this bulletin. These assumptions and statements have even crept into text-books. For example, Duggar 1909 (p. 317) says: "Smith and Swingle have by careful cultural and inoculation experiments demonstrated the causal connection of a *Fusarium* with these types of disease." In Germany the advocates of the fungus theory of the "Blattrollkrankheit" of the potato have gained most of their support from these assumptions.*

During the early stages of our investigations of this disease we critically examined the description by Smith and Swingle of a "Dry Rot of Potato due to *Fusarium oxysporum*" to determine the relationship between the disease there described and the dry rot found in Nebraska. Since no reference to inoculation experiments could be found in their bulletin the senior author wrote Dr. Smith to learn where their inoculation experiments were recorded. Dr. Smith replied that no inoculation experiments whatsoever had been made by the authors.

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* Appel and Schlumberger 1911 ((pp. 22, 23): "Da endlich Smith und Swingle Impfversuche beschreiben, bei denen es ihnen gelungen ist, ein der Blattrollkrankheit ganz ähnliches Bild mit ihrem *Fusarium oxysporum* zu erzeugen, so lag die Erklärung, die Blattrollkrankheit ebenfalls auf ein *Fusarium* zurückzuführen, sehr nahe."

Further, in a criticism of the enzym explanation of "Blattrollkrankheit" entertained by Sorauer, they say (p. 28): "Wenn aber Sorauer sagt, dass alle Forscher einen anderen Pilz als *Fusarium* gefunden haben, so hat er dabei eine der wichtigsten Arbeiten übersehen nähmlich die von Smith und Swingle (1904), die eine in ihren Erscheinungen der Blattrollkrankheit mindestens sehr ähnliche Krankheit auf *Fusarium oxysporum* zurückführen."

Delacroix* 1906 in a discussion of the black-leg of potatoes due to *Bacilius phytophthorus* expressed doubt as to the causal relation of *Fusarium oxysporum* to the wilt and dry rot described by Smith and Swingle.

COMPARATIVE STUDIES OF FUSARIUM OXYSPORUM AND FUSARIUM TUBERIVORUM.

In order to compare the behavior of the organism isolated from Nebraska tubers showing dry rot with the *Fusarium oxysporum* assigned by Smith and Swingle as the cause of a wilt and dry rot of the potato, we requested Dr. Smith to send us a culture of the organism with which he worked. Unfortunately these original cultures had died but Dr. Smith requested Mr. W. A. Orton, also of the Bureau of Plant Industry, to send cultures of an organism considered by him to be the same as the one with which Smith and Swingle had previously worked. This organism had been isolated by Orton from tubers, showing dry rot, secured from the Pacific Coast.

A close study of this *Fusarium oxysporum* and of the Nebraska *Fusarium* was undertaken in 1909 with special reference to the points which Smith and Swingle had emphasized. The relation of color formation to various kinds of light, to darkness, and to the kind of medium used was studied carefully. The influence of these factors upon the habit of the fungus was observed as well.

The work soon showed that the two organisms were not identical and the Nebraska fungus was set aside as a new species. The results of these studies are found in Tables 24 and 25.

MORPHOGENIC AND CHROMOGENIC INFLUENCE OF ACIDITY OF THE MEDIUM UPON FUSARIUM OXYSPORUM AND FUSARIUM TUBERIVORUM.

The solutions of the acids were made by dissolving the gram molecular weight of the acid in grams in water to make a liter of solution. These solutions are here referred to as N|1 solutions. Different amounts of these solutions were then added to the rice. For example, +100 acetic acid, as employed in the table, means that 5 c.c. of the N|1 solution were added to 50 c.c. of water and that 2 c.c. of this solution were added to 2 grams of rice kernels. The tubes were then autoclaved in a slanting position for 15 minutes at 110° C.

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* He says (p. 1353): "De plus, j'ai pu constater que le bactérie, qu'il s'agisse du *Bacillus solanicola*, aussi bien que du *Bacillus phytophthorus*, est presque toujours accompagnée d'un mycélium de *Fusarium;* ce mycélium, qui, d'après nos recherches, *n'est pas parasite*, n'apparait, dans un cas comme dans l'autre, que secondairement. On ne le rencontre pas sur la plante quand la maladie est à son début et j'incline à penser que les cas de parasitisme du *Fusarium oxysporum* récemment décrits en Amerique par E. F. Smith et D. B. Swingle sur la pomme de terre ne sont peut-être que des faits analogues à ceux que je décris."

The color numbers refer to the Repertoire de Couleurs published by the Société Francaise des Chrysanthemistes.

TABLE 24.—*Morphogenic and chromogenic influence of acidity.*

ACETIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+6.25	++	+	O	O	O	136:2	131:1-136:2
+6.25*	+	+	+	—	++	**196:1**	**131:2-195:4**
+12.5	++	+	O	O	O	136:2	131:1-136:2
+12.5*	++	+	+	—	++	**196:1**	**131:2-195:4**
+25	++	+	O	O	O	136:2	131:1-136:2
+25*	++	+	+	+	—	**196:1**	**131:2-194:4**
+50	O						
+50*	+	+	+	+	—	**196:1**	**131:2**
+100	O						
+100*	O						
+150	O						
+150*	O						

* Body type indicates *Fusarium oxysporum*; black type indicates ***Fusarium tuberivorum***.

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Continued.*

BUTYRIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+6.25	++	+	O	O	O	136:2	131:1-136:2
+6.25*	++	+	+	—	++	**196:1**	**131:2-194:4**
+12.5	++	+	O	O	O	136:2	131:1- 72:1
+12.5*	++	+	+	—	++	**196:1**	**131:2-194:4**
+25	+	+	O	O	O	136:2	131:1- 72:4
+25*	+	+	+	++	++	**196:1**	**131:2-194:4**
+50	O						
+50*	+	+	+	++		....	**131:2-194:4**
+100	O						
+100*	O						
+150	O						
+150*	O						

* Body type indicates *Fusarium oxysporum*; black type indicates *Fusarium tuberivorum.*

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Continued.*

CITRIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+25	++	+	+	—	++	136:2	131:1-136:2
+25*	+	+	O	O	O	**196:1**	**131:2**
+50	++	+	O	O	O	136:2	134:1-136:2
+50*	+	+	+	—	++	**196:1**	**131:2-194:4**
+100	++	+	O	O	O	136:2	136:2
+100*	++	+	O	O	O	**128:2**	**131:2-194:4**
+150	++	+	O	O	O	136:2	134:1
+150*	+	+	O	O	O	**196:1**	**131:2-194:4**
+200	++	+	O	O	O	136:2	131:2-134:3
+200*	+	+	+	++	++	**132**	**131:2-134:3**
+300	++	+	+	—	++	136:2	131:1-136:2
+300*	+	+	O	O	O	**196:1**	**131:2**

* Body type indicates *Fusarium oxysporum;* black type indicates *Fusarium tuberivorum.*

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Continued.*

FORMIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+6.25	++	+	O	O	O	136:2	
+6.25*	++	+	+	—	++	**196:1**	**131:3**
+12.5	+	+	O	—	O	136:2	131:3
+12.5*	++	+	+	—	++	**196:1**	**131:3**
+25	+	+	O	O	O	136:2	131:3
+25*	++	+	+	—	++	**128:2**	**131:3**
+50	+	+	O	O	O	136:2	131:3
+50*	++	+	+	++	++	**196:1**	**131:3**
+100	O						
+100*	O						
+150	O						
+150*	O						

* Body type indicates *Fusarium oxysporum;* black type indicates ***Fusarium tuberivorum.***

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Continued.*

HYDROCHLORIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+25	+	+	O	O	O	136:2	131:1
+25*	+	+	+	++	++	**196:1**	**131:1**
+50	—	+	O	O	O	136:2	131:1
+50*	+	+	+	—	++	**196:1**	**131:1**
+100	—	+	O	O	O	136:2	131:1
+100*	+	+	+	—	++	**White**	
+150	O						
+150*	O						

LACTIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+25	++	O	O	O	O	136:2	131:1
+25*	++	+	+	++	++		
+50	++	+	O	O	O	136:2	131:2-136:2
+50*	++	+	+	++	++	**196:1**	**132:2-128:4**
+100	++	+	O	O	O	136:2	131:1-136:2
+100*	++	+	+	++	—	**196:1-128:2**	**131:2-195:4**
+150	++	+	O	O	O	136:2	139:1
+150*	++	+	+	++	—	**196:1**	**131:2-195:4**

* Body type indicates *Fusarium oxysporum;* black type indicates ***Fusarium tuberivorum.***

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Continued.*

MALIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+25	++	+	O	O	O	136:2	139:2-136:2
+25*	++	+	+	++	++	**196:1**	**131:2-195:4**
+50	++	+	O	O	O	136:2	136:2
+50*	++	+	+	—	± +	**128:2**	**131:2-195:4**
+100	++	+	O	O	O	136:2	139:1
+100*	++	+	+	—	++	**128:2**	**132:1-195:4**
+150	++	+	O	O	O	136:2	132:1
+150*	++	+	+	—	++	**196:1**	**131:1-195:4**
+200	++	+	O	O	O	136:2	135:3
+200*	++	+	+	—	++	**196:1**	**131:1**
+300	++	+	O	O	O	136:2	135:3
+300*	++	+	+	+	++	**128:2**	
+400	++	+	O		O	136:2	135:3
+400*	++	+	+	—	—	**128:2**	**132:1-179**

NITRIC ACID

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
+50	++	+	O	O	O	136:2	131:1
+50*	++	+	+	—	—	**196:1**	**132:1-195:4**
+100	++	+	O	O	O	136:2	135:3
+100*	++	+	+	O	O	**196:1**	**132:1-195:4**
+150	O						
+150*	O						

* Body type indicates *Fusarium oxysporum;* black type indicates *Fusarium tuberivorum.*

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Continued.*

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
				OXALIC ACID			
+25	++	+	○	○	—	136:2	131:1
+25*	++	+	+	—	++	**196:1**	**132:1-195:4**
+50	++	+	○	○	○	136:2	135:3
+50*	++	+	+	+	++	**196:1**	**132:1-195:4**
+100	++	+	○	○	○	136:2	131:1
+100*	++	+	+	+	+	**196:1**	**132:1**
+150	○						
+150*	++	+	+	—	—	**196:1**	**135:3**
+200	++	+	○	○	○	136:2	132:1
+200*	++	+	+	—	++	**196:1**	**131:1**
				PHOSPHORIC ACID			
+25	++	+	○	○	○	136:2	135:3
+25*	++	+	+	+	+	**196:1**	**132:1-195:4**
+50	++	+	○	○	○	136:2	131:1
+50*	++	+	+	+	+	**196:1**	**132:1-179:1**
+100	++	+	○	○	○	136:2	131:1
+100*	++	+	+	+	+	**128:2**	**132:1**
+150	+	+	○	○	○	136:2	135:3
+150*	+	+	+	+	○	**128:2**	**132:1**
+300	—	+	○	○	○	136:2	131:1
+300*	++	+	+	+	○	**White**	**132:1-179:1**

* Body type indicates *Fusarium oxysporum*; **black type indicates** ***Fusarium*** *tuberivorum*.

TABLE 24.—*Morphogenic and chromogenic influence of acidity—Concluded.*

Acidity	Growth	Macroconidia	Microconidia	Chlamydospores	Sclerotia	Color in dark	Color in light
SULFURIC ACID							
+25	+	+	○	○	○	136:2	135:3
+25*	+ +	+	+	+	+ +	**196:1**	**132:1-195:4**
+50	−	+	○	○	○	136:2	131:1
+50*	+ +	+	+	+	+	**128:2**	**132:1-195:4**
+100	−	+	○	○	○	136:2	131:1
+100*	+	+	+	−	○	**128:2**	**132:1**
+150	○						
+150*	○						
TARTARIC ACID							
+25	+ +	+	○	○	○	136:2	131:1-136:2
+25*	+ +	+	+	+	+ +	**196:1**	**132:1-195:4**
+50	+ +	+	○	○	○	136:2	131:1-136:2
+50*	+ +	+	+	+ +	−	**196:1**	**132:1-195:4**
+100	+ +	+	○	○	○	136:2	135:3
+100*	+ +	+	+	+	−	**196:1**	**132:1-195:4**
+150	+ +	+	○	○	○	136:2	131:1
+150*	+ +	+	+	+	+ +	**196:1**	**131:1-195:4**
+200	+ +	+	○	○	○	136:2	131:1-136:2
+200*	+ +	+	+	+	+	**196:1**	**132:1**
+300	+ +	+	○	○	○	136:2	131:1-136:2
+300*	+	+	+	+	−	**196:1**	**132:1**
± 400	+	+	+	+ +	+ +	196:1	132:1
CHECK							
	+ +	+	○	○	○	135:3	136:2
	+ +	+	+	+	+ +	**132:1-195:4**	**132:1-195:4**

* Body type indicates *Fusarium oxysporum;* black type indicates *Fusarium tuberivorum.*

CHROMOGENIC INFLUENCE OF LIGHT UPON FUSARIUM OXYSPORUM AND FUSARIUM TUBERIVORUM.

Solutions of copper sulfate and ammonium hydrate and of potassium bichromate were made in the ordinary manner to provide screens for the development of the blue and the yellow light respectively. Other cultures were placed in the incubator and others exposed to sunlight. In general we note that our *Fusarium tuberivorum* did not respond quite so readily to the light factor as is reported for *Fusarium oxysporum* by Smith and Swingle. (See Table 25.)

TABLE 25.—*Showing the resulting color of Fusarium oxysporum and Fusarium tuberivorum when grown in various media in blue light, yellow light, sunshine, and darkness for a period of 14 days.*

Media	Blue light	Yellow light	Sunshine	Darkness
Boiled rice	Salmon	Salmon	Salmon	Light salmon
	Lilac pink	Lilac pink	Lilac pink	White
Potato agar	Light salmon	Light salmon	Light salmon	White to pure salmon
	Delicate pink	White	Delicate pink	White
Peptone potato	Salmon	Salmon	Salmon	Light salmon
	White	White	Light salmon	White
Agar banana	Salmon	Salmon	Salmon	Salmon
	Rosy pink	Deep rosy pink	Rosy pink	White to rosy pink
Rhubarb	Light salmon	Light salmon	Light salmon	Light salmon
	White	White	Light pink	Light pink
Boiled potato	Salmon	Salmon	Salmon	Light salmon
	Light pink	White	Light pink	White

The data in the above table and other unpublished data show rather clearly that the organism sent us by Orton as the *Fusarium oxysporum* of Smith and Swingle differs from the *Fusarium tuberivorum* in several important particulars. Consequently as early as 1909 the Nebraska organism was considered in this laboratory a new or undescribed species and a tentative name had been given to it.

Smith and Swingle 1904 combined *Fusarium solani, Fusarium pestis, Fusarium oxysporum,* and other species of this genus. found on potatoes, under the name *Fusarium oxysporum.*[*]

Appel and Wollenweber 1910[†] examined a culture of *Fusarium oxysporum* sent them by Orton from Oregon potatoes, and decided that this organism should be called *Fusarium orthoceras.*

RESISTANCE AND SUSCEPTIBILITY.

During the winter of 1911-1912 extensive experiments were conducted to determine the comparative resistance of tubers of different varieties of potatoes to invasion by this fungus. Tho the detailed results of these and many previous similar ones are reserved for future publication, it seems well here to present the general results. From Colorado, thru the kindness of F. L. Fitch, were secured the following sorts:

1. Bliss Triumph
2. Burbank
3. Early Ohio
4. Early Rose
5. Gold Coin
6. Green Mountain
7. Norton's Beauty
8. Pearl
9. Raleigh
10. Russet
11. White Ohio

From Minnesota, thru the kindness of A. R. Kohler of the Minnesota Experiment Station, were secured tubers of the following sorts:

1. Early Ohio
2. Raleigh

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[*] Lindau 1908 questions the wisdom of this treatment (p. 470), and says: "Man kann bei den verschiedenen Symptomen, welche die drei beschriebenen Krankheiten haben, zweifelhaft sein, ob man dieser Ansicht beipflichten soll; * * * Man tut wohl am besten, bis durch Kultur und Impfung dieser Punkt geklärt ist, die Verschiedenheit der Krankheiten und ihrer Erreger noch aufrecht zu erhalten."

[†] (*L. c.*, page 146). "Um völlig sicher zu gehen, dass beide Pilze identisch sind, erbaten wir eine Kultur des *F. oxysporum* der Verfasser. Wir erhielten eine solche durch die Güte des Herrn E. F. Smith, zwar nicht eine Originalkultur, sondern eine in Oregon von Herrn W. A. Orton aus 'Dry rot'—kranken Kartoffeln gezüchtete Art. Die letztere war im Reagensglase verschlossen Herrn Smith nach Washington zur Diagnostizierung übersandt worden, wurde aber den 27. IV. 1909 uneröffnet nach Deutschland weitergeschickt als vermutlich *F. oxysporum* Smith und Swingle."

Sound tubers, previously sterilized with corrosive sublimate, were placed in contact with thoroly rotted tubers. In not a single case did infection of the sound tubers result.

Inoculum was placed over lenticels and over the "eyes" but no infection resulted in any of the varieties. In no case did infection occur.

Sound tubers were sterilized with corrosive sublimate and inoculated thru a wound. None of the varieties mentioned above escaped infection but there was evident some slight difference as to the extent of the rotting in the different sorts. These results fully confirm those previously secured. (See Plates I to XII.)

OTHER INOCULATIONS.

In the winter and spring of 1911-1912 experiments were conducted to determine the comparative resistance of aerial stems of various varieties of potatoes to the invasion of *Fusarium tuberivorum*. The following sorts were obtained from Colorado thru the kindness of F. L. Fitch of the Colorado Experiment Station:

1. Raleigh
2. Early Rose
3. Burbank
4. White Ohio
5. Early Ohio
6. Russet
7. Bliss Triumph
8. Norton's Beauty
9. Gold Coin
10. Pearl
11. Green Mountain
12. Spaulding's Rose
13. Beauty of Hebron
14. Snowflake

From Minnesota, thru the kindness of A. R. Kohler, were secured tubers of the following sorts:

1. Raleigh
2. Early Ohio

These tubers, previously sterilized by soaking in corrosive sublimate solution (1 to 1000) for one-half hour, were planted in soil which had been previously sterilized by steaming in pots which had been sterilized with formalin solution. These pots were kept in the greenhouse and watered, as need arose, with distilled water.

When the plants had attained a height of about 30 to 35 cm. inoculation was attempted. In each pot some stems were wounded quite deeply with a sterile scalpel before the inoculum was applied. This inoculum consisted of a mixture of spores, hyphae, and glucose agar. Other stems were merely smeared with the inoculum without previous wounding. Four stems in each pot were used for the experiment, two with wounds and two without wounds. The humidity of the atmosphere in the greenhouse was kept as high as possible during the inoculation and immediately following it so that conditions for germination of spores and hyphal development might be as favorable as possible.

No infections resulted from the 64 inoculations. In many cases the fungus flourished on the stems and in the wounds for a considerable period. On one stem a slight browning developed but no fungus developed in the stem. The wounded stems promptly developed wound cork which very often sloughed off with the inoculum tho in many the inoculum persisted until the death of the stems. In several cases the fungus renewed its growth as soon as the stems died, but in not one did the fungus enter the stem and cause a wilt. Several stems were bruised so severely at the time of inoculation that they soon toppled over and either lived on in this prostrate position or died by strangulation. Such dead stems were promptly overrun by the fungus.

Following these failures in producing the wilt of the stems, the experiments were repeated on younger stems of the same plants. No infections could be obtained.

Some vines of the Pearl variety were bruised with a sterile scalpel by cutting out a piece of the bark deep enough to expose the wood. Inoculum was smeared into these wounds, which were then covered with moistened sterile cotton which was kept moist for a week with sterile water. Wound cork was formed both in the inoculated and control stems but no infection set in. Twelve inoculations were made and all were unsuccessful in producing any wilt. Upon death of the stems the fungus lived upon them saprophytically.

These experiments show quite conclusively that the fungus cannot infect aerial, living stems of the potato, either thru wounds or thru the epidermis. The experiments also show that the fungus does attack stems as soon as they are dying or dead. (See Pls. XII to XXI.)

Appel and Schlumberger 1911 refer to certain infection experiments with the *Fusarium oxysporum* of Smith and Swingle conducted by Köck 1909.*

We have previously discussed certain results which show clearly considerable variation in the susceptibility of the tubers of different varieties to the dry rot. The explanation for this may be found in one of several factors which may here be mentioned. The short growing season for potatoes in western Nebraska and particularly the frequent occurrence of killing frost before the vines have fully matured may be sufficient to account for the presence of a thinner and more readily penetrable skin than might be found under other circumstances. A histological examination of tubers from various sources tends to support this explanation tho further studies are required to put the matter beyond doubt.

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* They say (p. 24): "Auffallend ist bei seinen Versuchen, dass auch die Infectionen mit Originalkulturen des Erregers des dry rot, *Fusarium oxysporum*, nicht gelangen. Diese Impversuche fussen im wesentlichen auf der ursprünglichen Annahme Appels, dass die Eingangspforte für die erste Infektion der unterirdische Teil des Stengels sei."

The failure of stem inoculations, or at least the very weak infection there found, would lead one to suppose that there was some substance in the stem, not found in the tuber, which tended to render the stem more immune against invasion by this fungus. The further fact that young tubers are infected neither in the field nor readily in the laboratory is still further evidence of this same sort. The distribution of solanin in the different parts of the potato plant is known to agree fairly well with the observed facts of inoculation. The exact relationship of solanin distribution and its relative abundance in different parts of the same variety of potato and in different varieties is now being investigated in this laboratory.

It should be stated that it has been shown by one of our colleagues* that the continuous growing of potatoes in the hot soil of eastern Nebraska apparently tends to result in weakened vigor. This tendency may be largely overcome thru the use of a mulch or the importation of seed from a cooler climate. Just what, if any, effect these conditions may have upon the development of the skin or the distribution of solanin remains to be determined.

METHODS OF CONTROL.

The following experiments were conducted to learn if any method of treatment might be employed by which the rotting of the tubers during storage might be largely or entirely prevented. Arrangements were made to conduct these experiments in the cement potato cellar of Lincoln Davis near Gordon, Nebraska, and to him we are indebted for his enthusiastic interest and assistance in this phase of the investigation. A total of eighty-one bushels were employed in the experiment and these were divided into ten lots of about eight bushels each and treated before being placed in storage, as follows:

1. Flowers of sulfur. The tubers were rolled in this powder so that their entire surface was covered.
2. Air-slaked lime. The tubers were thoroly dusted over with this powder.

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* Emerson, R. A., Bul. 97 Nebr. Agr. Exp. Station.

3. Lime and sulfur. The tubers were dusted over with a powder composed of three parts of air-slaked lime and one part of the flowers of sulfur.
4. Lime-sulfur wash. This was made by boiling in the usual manner five pounds of sulfur, five pounds of lime, and fifteen gallons of water. After treatment the potatoes were dried before being placed in the storage bin.
5. Formic aldehyde solution. The tubers were placed in sacks and dipped for two hours in a solution of one pint of 40 per cent formic aldehyde solution (often called "formalin") in a barrel of water. The tubers were then dried before being placed in storage.
6. Formic aldehyde vapor. The tubers were exposed to the vapors generated by twenty-three ounces of potassium permanganate placed in three pints of a 40 per cent solution of formic aldehyde (formalin) to each one thousand cubic feet of space.
7 Check. These tubers were not treated at all.
8. Check. These tubers were wounded by walking over them before they were placed in storage.

The tubers were placed in bins two feet wide and five feet long and were about three feet deep in each of these bins. The bins had previously been thoroly disinfected with formic aldehyde solution. Treatment was applied and the potatoes were stored October 1 and the counts were made the following April 25. The results are shown in Table 26.

In the first eight lots the World's Fair potato was employed, while for two of the checks smaller lots of the Blue Victor and the Early Ohio were employed.

TABLE 26.—*Results of experiments in the control of dry rot.*

Treatment	Total number of tubers	Number rotted	Per cent rotted
1. Flowers of sulfur	1108	133	12.00
2. Lime	1393	227	16.08
3. Lime and flowers of sulfur	1208	291	24.08
4. Lime-sulfur wash	1420	45	3.16
5. Formalin dip	1221	60	4.09
6. Formalin vapor	1459	67	4.59
7. Check—not bruised	1121	182	16.23
8. Check bruised	1262	397	31.46
9. Check—Early Ohio	1000	316	31.60
10. Check—Blue Victor	641	67	10.45

This experiment has clearly demonstrated that dry rot during storage may be held in check thru treatment of the tubers before being placed in the storage cellars. For this purpose the best results were secured thru the use of either formalin dip, formalin vapor, or the lime-sulfur wash. Not only did the tubers in these lots show a very small percentage of dry rot but the tubers themselves were in excellent condition otherwise when removed in April. The storage time, it should be remembered, employed in this experiment is longer than would ordinarily be employed by the average farmer and this gave the treatments a severe test. Under ordinary farm conditions the development of the formalin vapors is not easily secured and therefore we would particularly recommend the use of the formalin dip as the easiest method to employ and one that should give excellent results in practice.

In connection with the above experiment a quantity of the World's Fair tubers were selected that showed bundle blackening or stem-end rot. The stem ends of these tubers were cut away till none of the discolored tissue remained. These tubers were then stored for the same length of time with the lots above mentioned with the following results:

TABLE 27.—*Effect of removal of the discolored stem ends.*

Total number of tubers	Number showing stem-end rot	Per cent showing stem-end rot	Number showing dry rot	Per cent showing dry rot
1129	24	2.14	426	37.73

This experiment clearly shows that the removal of the stem end of tubers showing characteristic stem-end rot tends thru wounding the tubers to greatly increase the amount of rotting due to dry rot and hence could not be practiced with safety in the control of the bundle blackening.

SUMMARY AND CONCLUSIONS.

1. The dry rot of the Irish potato tuber herein described is primarily a disease of mature tubers.

2. This rot is of great economic importance thru the serious destruction of the tubers while in winter storage.

3. This dry rot has been shown by numerous infection experiments to be due to a new species of *Fusarium*, herein described under the name *Fusarium tubcrivorum* sp. n. Wilcox and Link.

4. This fungus has been shown to be incapable of infecting any other part of the potato plant than the tuber.

5. This fungus cannot invade the tuber until it has practically attained maturity and then only thru wounds. Infection thru scab spots, lenticels, or the eye seems to be impossible. During

the winter, the tuber is destroyed more rapidly by this dry rot than at harvest time.

6. It has been found possible to greatly reduce the amount of dry rot by proper fungicidal treatment before the tubers go into storage. Wounded tubers had best not be stored with sound tubers.

BIBLIOGRAPHY.

ANON.

1906. Winter-rot of Potatoes (*Nectria solani* Pers.). Jour. Bd. Agr. **13**: 739-740. 1 figure.

APPEL, O.

1906. Neuere Untersuchungen über Kartoffel- und Tomatenerkrankungen. Jahrb. Ver. angew. Bot. **3**: 122-136. Figs. 1-2.

APPEL, O., und SCHLUMBERGER.

1912. Die Blattrollkrankheit und unser Kartoffelernten. Arb. deut. landw. Gesell. **190**: 1-102. Pls. 1-3.

APPEL, O., und WOLLENWEBER, H. W.

1910. Grundlagen einer Monographie der Gattung *Fusarium* (Link). Arb. K. biol. Anst. Land- u. Forstw. **8**: 1-207. Pls. 1-3, figs. 1-2.

BESSEY, C. E.

1899. Report of the Botanist. Rpt. Nebr. Exp. Sta. **1898**: xxvii.

BREFELD, O.

1888. Untersuchungen aus dem Gesamtgebiete der Mykologie. **7**.

1889. Untersuchungen aus dem Gesamtgebiete der Mykologie. **8**.

1905. Untersuchungen aus dem Gesamtgebiete der Mykologie. **14**.

BUTLER, E. D.

1909. Dry Rot *(Fusarium solani vel oxysporum)*. Agr. Gaz. New South Wales **20**: 708-709. Fig. 6.

CLINTON, G. P.

1895. Dry End Rot. Bul. Ill. Exp. Sta. **40**: 139-140.

1904 Dry Rot, *Fusarium oxysporum* Schl. (*F. solani* (Mart.) Sacc.). Rpt. Conn. Exp. Sta. **1903**: fig. *b* on pl. 22.

CORDA, A. C. J.

1829. Pilze in J. Sturm's Deutschland's Flora **7**, **8**, **9**. Pls. 17-64.

1837. Icones Fungorum hucusque cognitorum. **1**: 32 pp., 7 plates.

Delacroix, G.

1906. La maladie bacterienne de la pomme de terre produite par le *Bacillus phytophthorus* (Frank) O. Appel. Bul. Men. Office Renseig. Agr. **5**: 1352-1355.

Frank, A. B.

1898. Die *Fusarium*-Fäule. Ber. deut. bot. Gesell. **16**: 279-280.

Fries, E. M.

1849. Summa vegetabilium Scandinaviae. Sectio posterior 259-572.

Jack, R. W.

1910. Root Gall Worm in Potatoes. Rhodesian Agr. Jour. **7**: 1533-1534. 2 figures.

Johnson, T.

1907. Fusarium. Econ. Proc. Roy. Dublin Soc. **1**: 353.

Jones, L. R.

1912. Potato Diseases in Wisconsin and Their Control. Circ. of Inform. Wis. Exp. Sta. **36**: 1-10.

Kirk, T. W.

1905. Dry-rot *(Fusarium oxysporum)*. Bul. Div. Biol. and Hort. New Zealand Dept. Agr. **7**: 18-19.

1907. Dry-rot *(Fusarium oxysporum)*. Rev. Edit. Bul. Div. Biol. and Hort. New Zealand Dept. Agr. **7**: 27-28.

Köck. G.

1909. Unsere gegenwärtigen Kenntnisse über die Blattrollkrankheit der Kartoffel. Monatshefte f. Landw.

Lawrence, W. H.

1907. Dry rot of potatoes (*Fusarium orxysporum* Schl.). Bul. Wash. Exp. Sta. **87**: 40-43. Fig. 15.

Link, H. F.

1809. Observationes in ordines plantarum naturales. Mag. Gesell. naturf. Freunde **3**: 3-42.

1824. Species Hyphomycetum et Gymnocetum. Pars 1.

Lindau, G.

1908. Die pflanzlichen Parasiten. Sorauer's Handb. d. Pflanzenkr. **2**: 1-550, figs. 1-62.

LOUNSBURY, C. P.

1909. Dry rot of the potato. Agr. Jour. Cape Good Hope **35**: 42-48. 3 figures.

MANNS, T. F.

1911. The *Fusarium* Blight and Dry Rot of the Potato. Bul. Ohio Exp. Sta. **229**: 299-336. Pls. 1-15.

MOLZ, E.

1907. Untersuchungen über die Kartoffelfäule. Ber. K. Lehranst. f. Wein-, Obst- u. Gartenbau zu Geisenheim **1906**: 172-176.

MORSE, W. J.

1909. Stem and Tuber Diseases. Bul. Me. Exp. Sta. **164**: 2-3.

1910. The *Fusarium* Dry Rot. Circ. Me. Exp. Sta. 6-7.

NIJPELS, P.

1897. Pourriture des pommes de terre. Bul. Soc. Roy. Bot. Belgique **36**^{2}: 194-198.

NORTON, J. B. S.

1906. Dry Rot. Bul. Md. Exp. Sta. **108**: 67.

OBERTHUER, R.

1905. Repertoire de Couleurs publie par la Société Francaise des Chrysanthemistes.

ORTON, W. A.

1909. Potato Wilt. Circ. Bur. Pl. Ind. U. S. Dept. Agr. **23**: 4-8.

PETHYBRIDGE, G. H., and BOWERS, G. E. H.

1908. Dry Rot of the Potato Tuber. Econ. Proc. Roy. Dublin Soc. **1**: 547-558. Pl. 48.

PIZZIGONI, A.

1896. Cancrena secca ed unida delle patate. Nuovo Gior. Bot. Ital. **3**: 50-53.

PRICE, R. H.

1897. Dry Rot *(Fusarium solani)*. Bul. Texas Exp. Sta. **42**: 926. Fig. 5.

ROLFS, F. M.

1905. Dry Rot, *Fusarium oxysporum* (Schlechtendahl). Rpt. Fla. Exp. Sta. **1905**: 40-41.

ROLFS, P. H.

1901. Irish Potato Summer Rot *(Fusarium?)*. Rpt. S. Car. Exp. Sta. **1900**: 26.

SACCARDO, P. A.

1886. Sylloge fungorum omnium hucusque cognitorum. **4**: 705.

SCHLECHTENDAHL.

1824. Flora Berolinensis.

SELBY, A. D.

1910. Dry-Rot. Bul. Ohio Exp. Sta. **214**: 432. Figs. 81, 83.

1910. Fusarium Blight. Bul. Ohio Exp. Sta. **214**: 432-434. Figs. 81, 83.

1910. Examine your seed potatoes for dry-rot. Press Bul. Ohio Exp. Sta. **311** and Bul. Ohio Exp. Sta. **220**: 663-664.

SMITH, E. F., and SWINGLE, D. B.

1904. Dry Rot of Potato Due to *Fusarium oxysporum*. Bul. Bur. Pl. Ind. U. S. Dept. Agr. **55**: 1-64. Pls. 1-8. Figs. 1-2.

STEWART, F. C.

1896. A new *Fusarium* on potato stems. Bul. N. Y. Geneva Exp. Sta. **101**: 85-86.

1897. The communicability of potato stem-blight. Bul. N. Y. Geneva Exp. Sta. **138**: 632-634.

STEWART, F. C., and EUSTACE, H. J.

1904. Dry Rot. Farmers' Inst. Lecture, Office Exp. Stations, U. S. Dept. Agr. **2**: 7-8.

SUTTON, A. W.

1898. Rust, Curl, or Dry Rot. Jour. Roy. Hort. Soc. **9**: 598-599. Fig. 29.

TIDSWELL, E.

1910. Dry Rot. Rpt. Govt. New South Wales Bur. Microbiology **1909**: 60-61. Illust.

WEHMER, C.

1896. Über die Ursache der sogenannten "Trockenfäule" der Kartoffelknollen. Ber. deut. bot. Gesell. **14**: 101-107. Figs. 1-3.

1897. Ansteckungsversuche mit *Fusarium solani* (Die *Fusarium*-Fäule). Centralbl. f. Bakt. u. Par. **3**: 727-743. Pls. 10, 11.

PLATE I

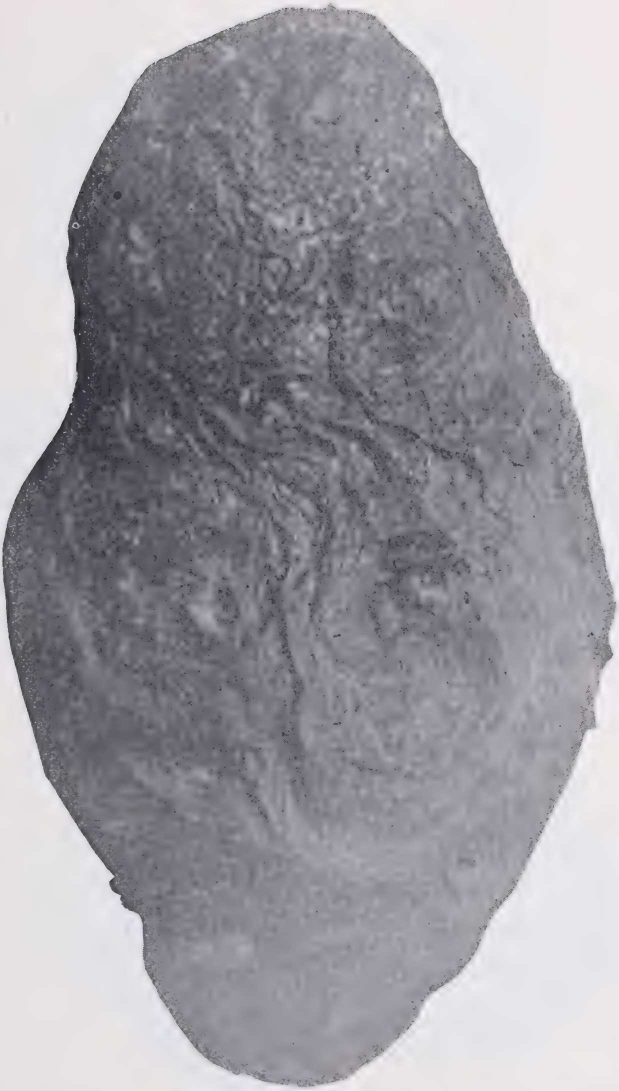

Plate I. Shows the characteristic shrivelling and wrinkling of the surface of the tuber and the sporodochia-like pustules which have broken thru the surface of the rotted area. Photographed six weeks after inoculation. Natural size.

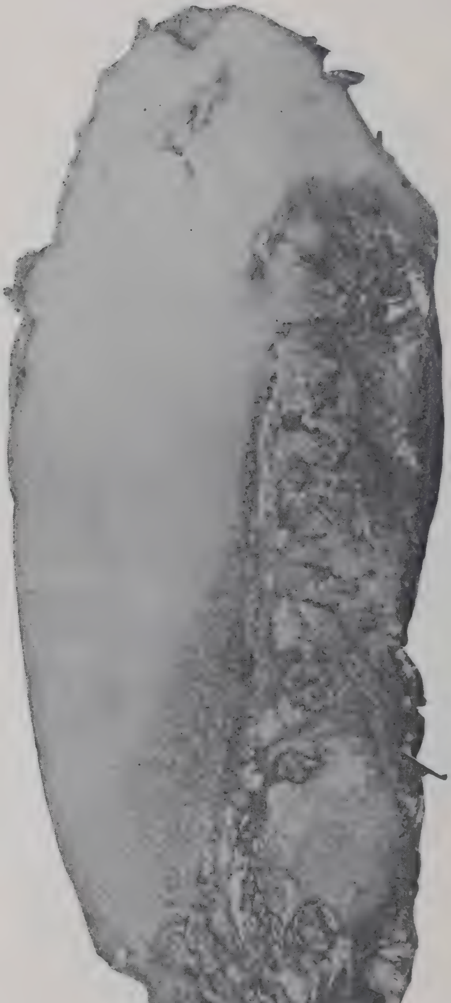

Plate II. Longitudinal section of a rotted tuber. Bacteria have here entered and caused a wet rot and brown discoloration in advance of the dry rot due to *Fusarium*. Photographed six weeks after inoculation. Natural size.

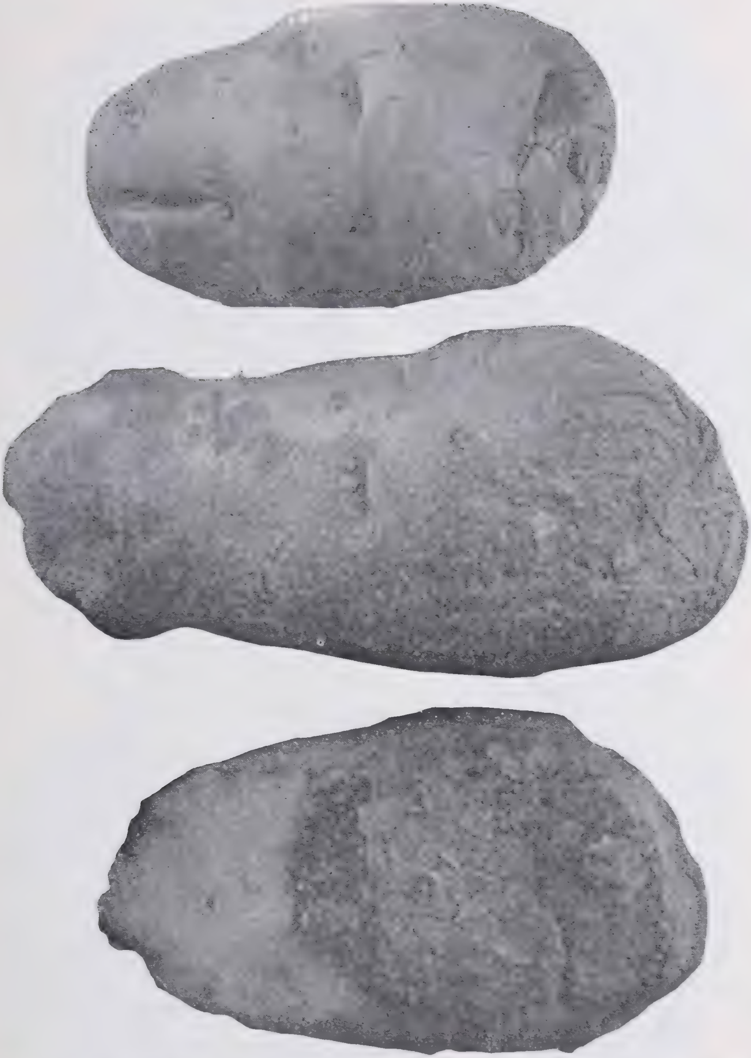

Plate III. Shows the characteristic appearance of the rot from the surface. No exterior signs of the fungus are evident. When the tubers are kept in a dry place the fungus grows entirely within the tuber. Photographed six weeks after inoculation.

PLATE IV

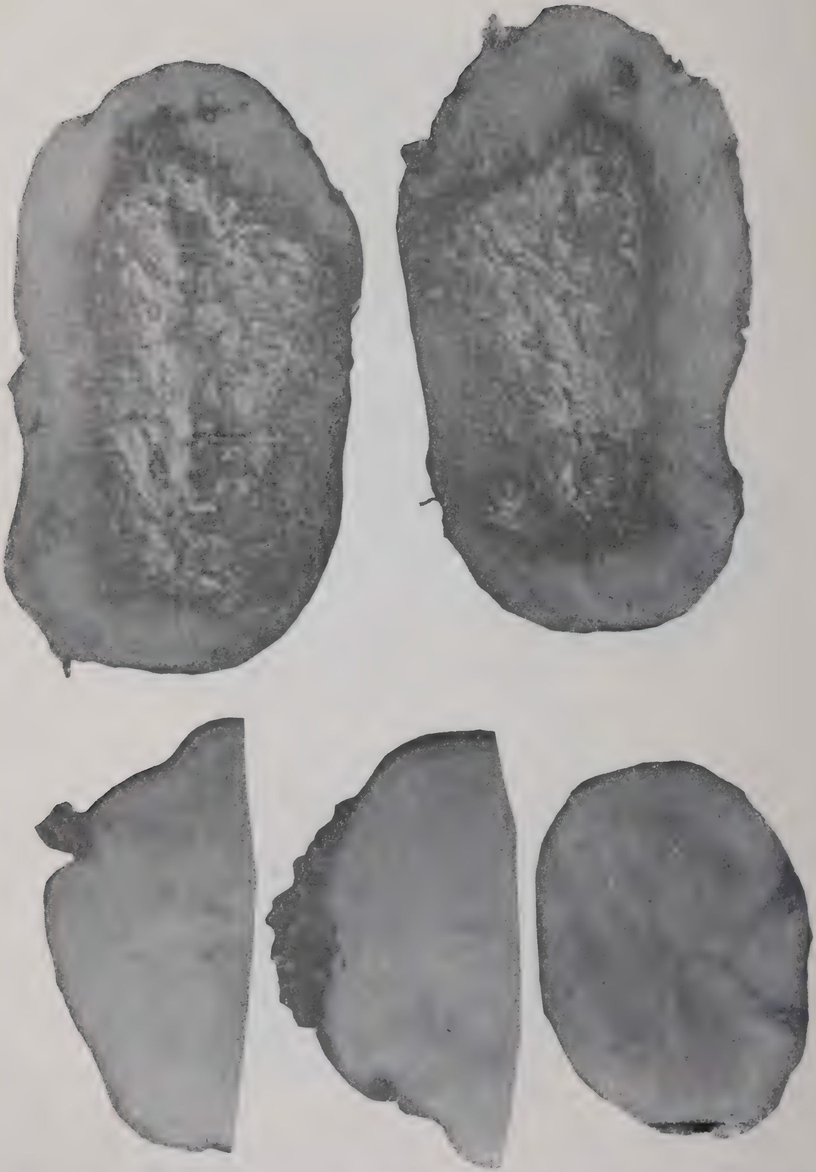

Plate IV. The upper tubers show the result of puncture inoculation; the lower ones show the failure of eye surface application of the inoculum.

PLATE V

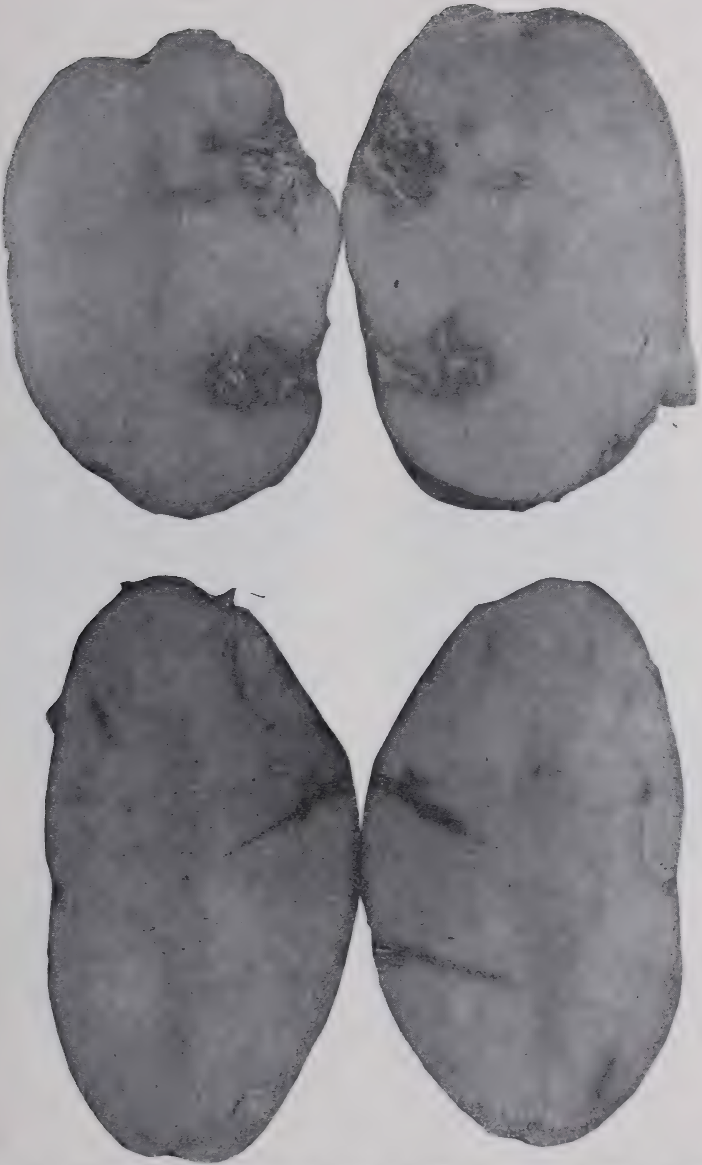

Plate V. Upper tuber incculated and lower punctured with a sterile needle. Both were then cut open thru the puncture. Photographed six weeks after inoculation.

PLATE VI

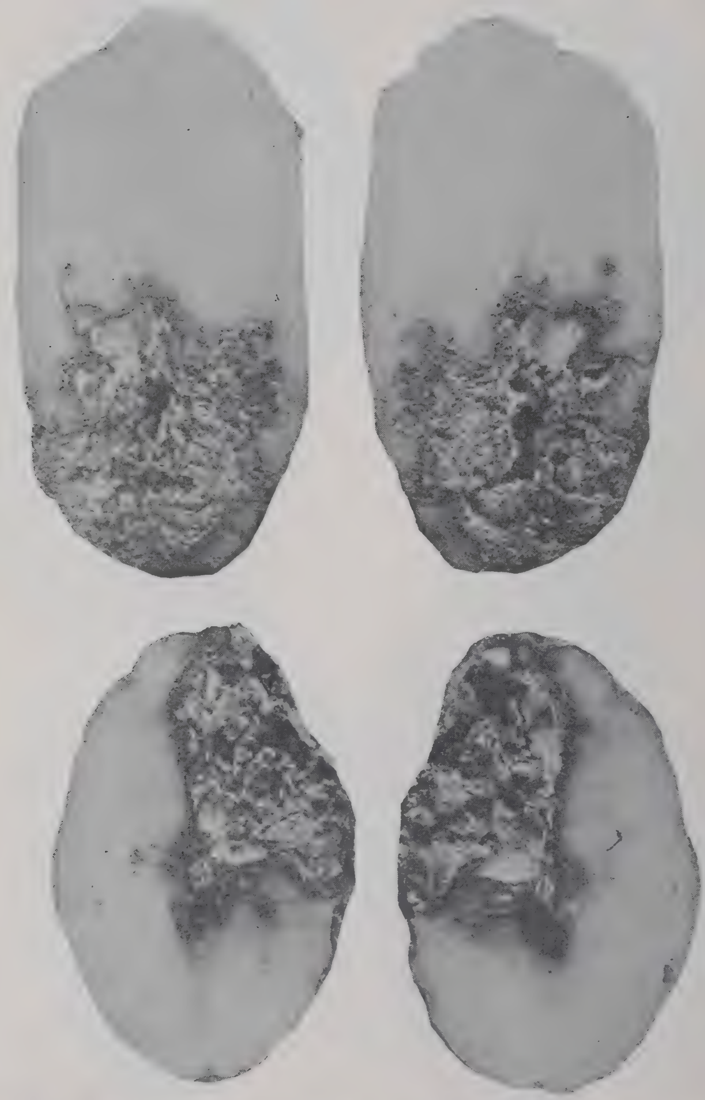

Plate VI. Characteristic development of dry rot following inoculation thru a puncture. The tubers were cut open to show the details and extent of the rotting.

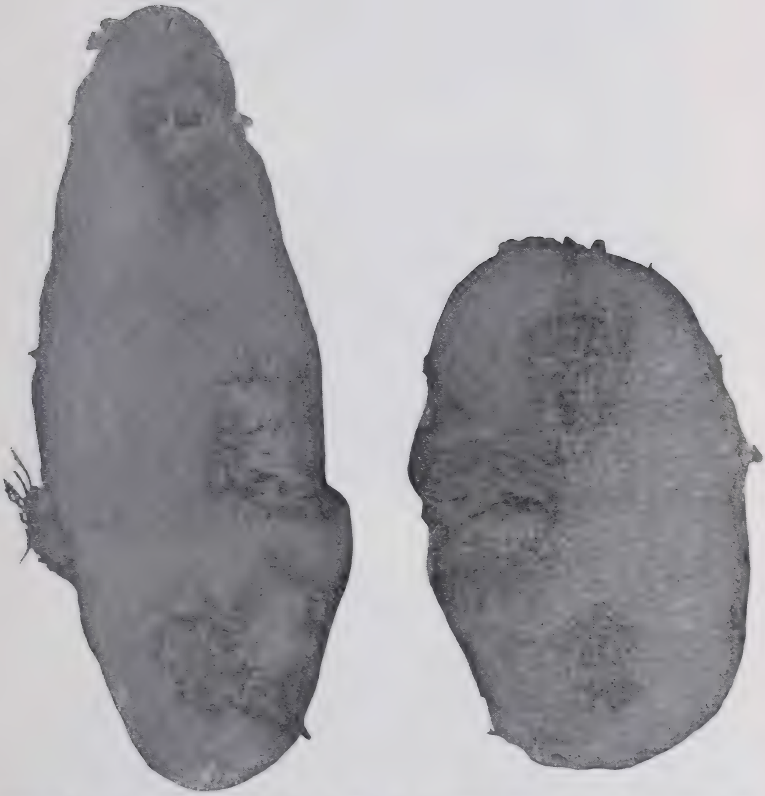

Plate VII. Development of dry rot in tubers kept in the refrigerator in a humid atmosphere. The longer tuber is the Burbank; the shorter one is Early Ohio. Photographed four weeks after inoculation.

PLATE VIII

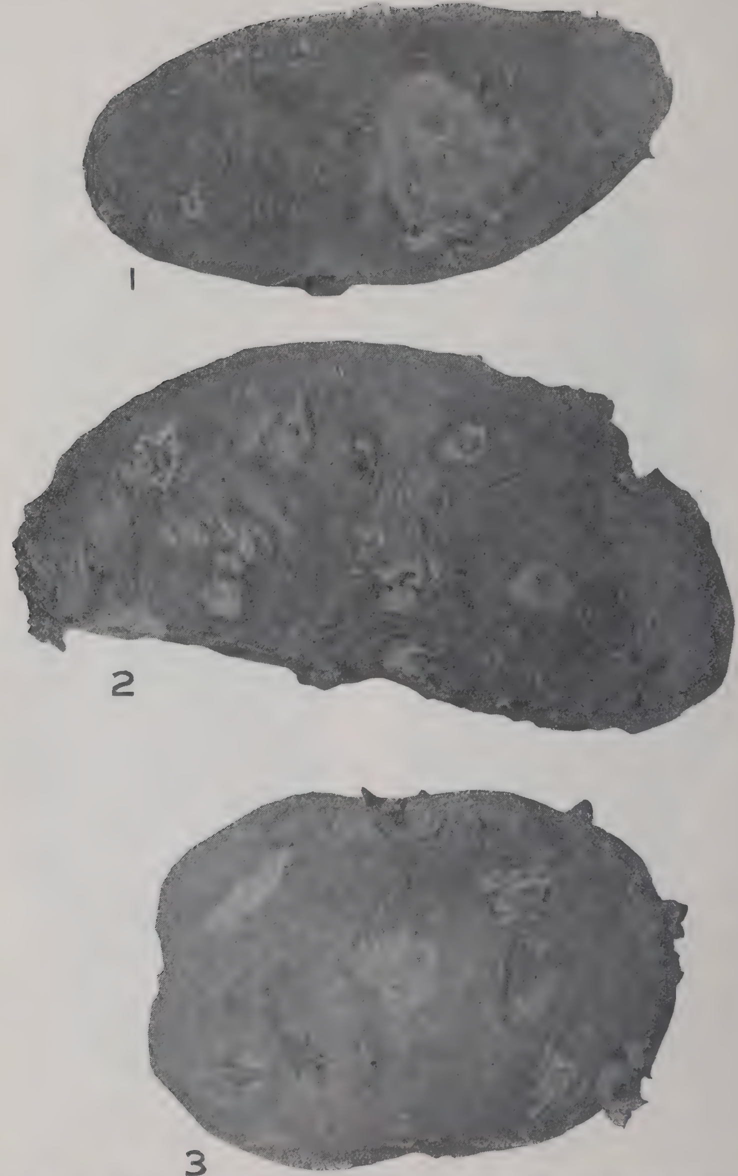

Plate VIII. Tubers showing a slight amount of rotting at the inoculation points. These were kept in the refrigerator in a humid atmosphere. Photographed four weeks after inoculation.

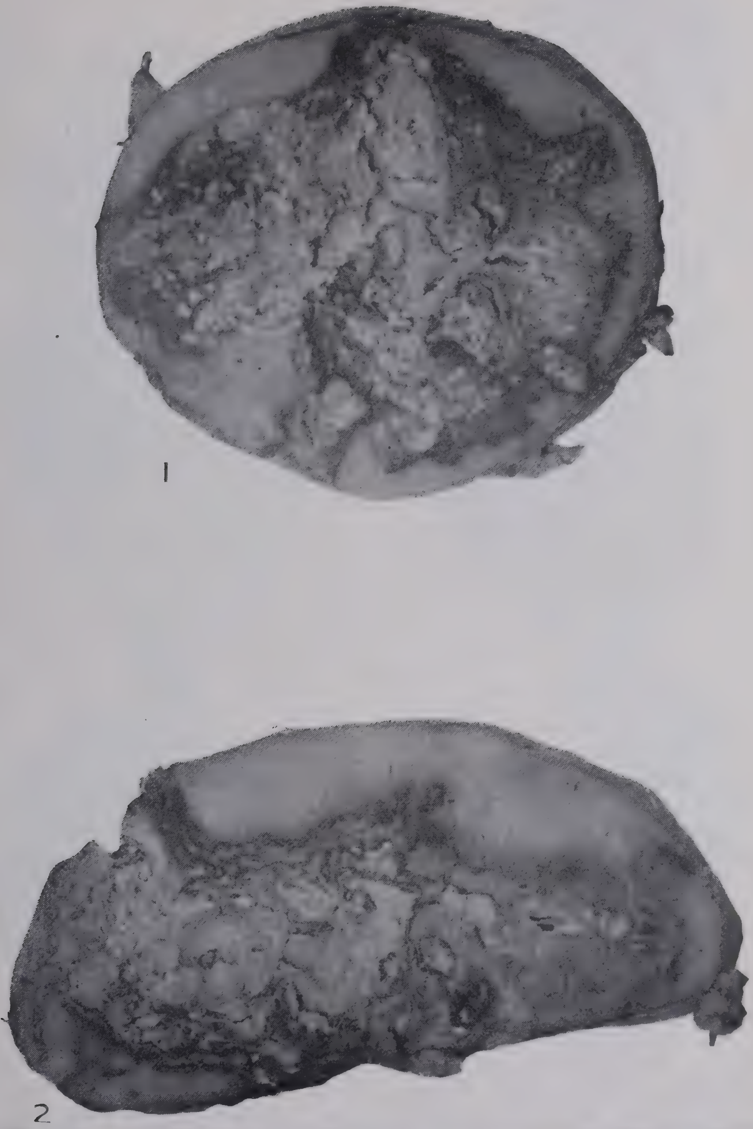

Plate IX. Photographs of tubers cut open six weeks after inoculation. This shows an extensive rotting of the tubers. No. 1 is the Pearl and No. 2 is the Burbank.

PLATE X

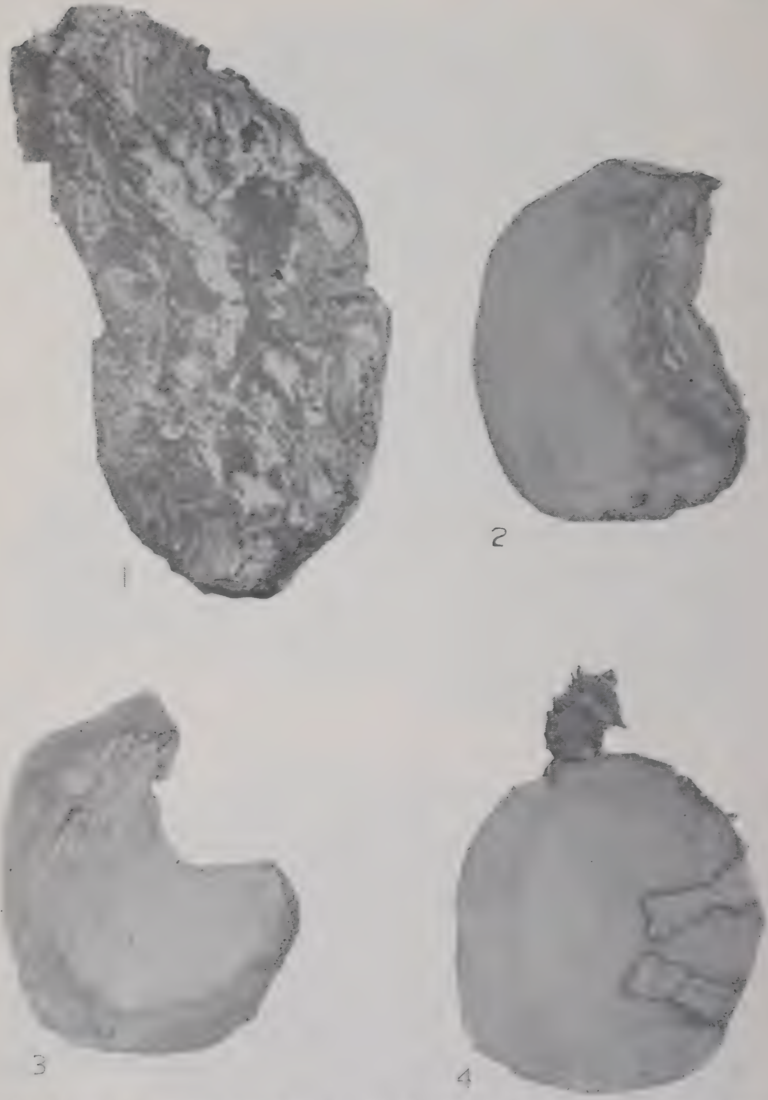

Plate X. Fig. 1 shows the final stage of dry rot in which the entire tuber is converted into a dry mass of tissue remnants, starch, hyphae, and spores. This tuber was kept in the laboratory on a table after inoculation. Fig. 2 shows the characteristic appearance of the rotted region. This is an Early Ohio tuber kept in the refrigerator in humid air. Fig. 3 shows the exterior of the tuber shown in Fig. 2. Here is a copious development of the fungus on the outside of the tuber. Fig. 4 shows slight development of the rot in a deep inoculation puncture. All photographed six weeks after inoculation.

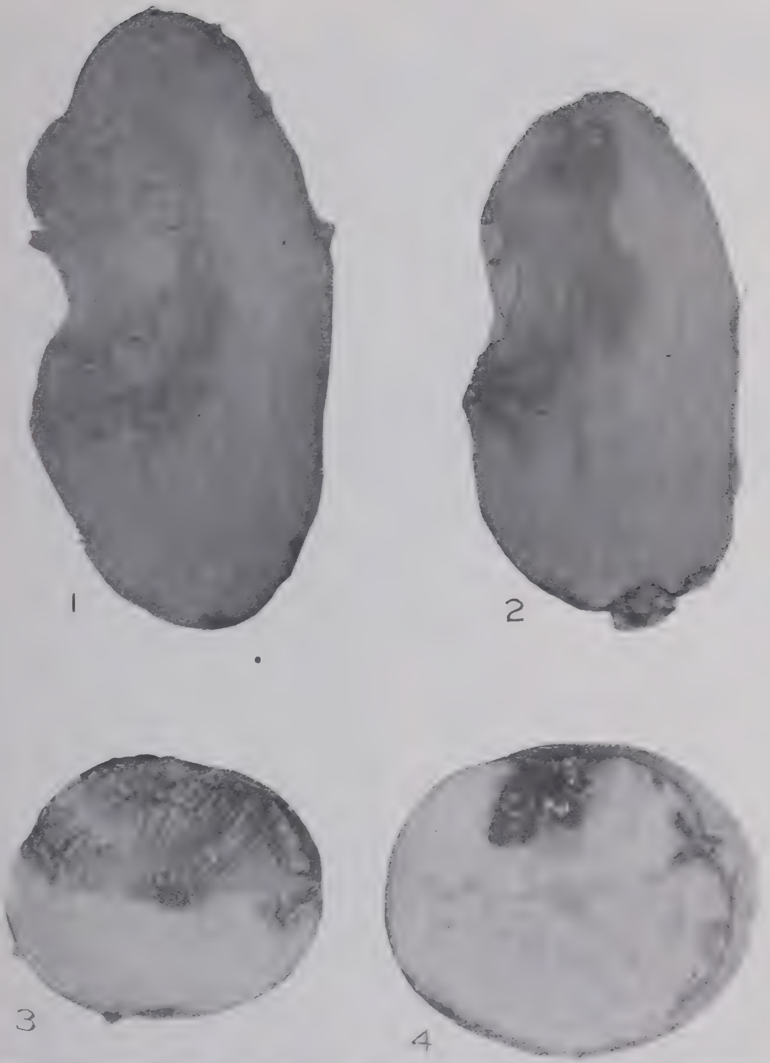

Plate XI. Sections showing characteristic bacterial contamination following inoculation. Early Ohio tubers. The tissue is soft and discolored because of this bacterial invasion in advance of the *Fusarium*. Photographed six weeks after inoculation.

PLATE XII

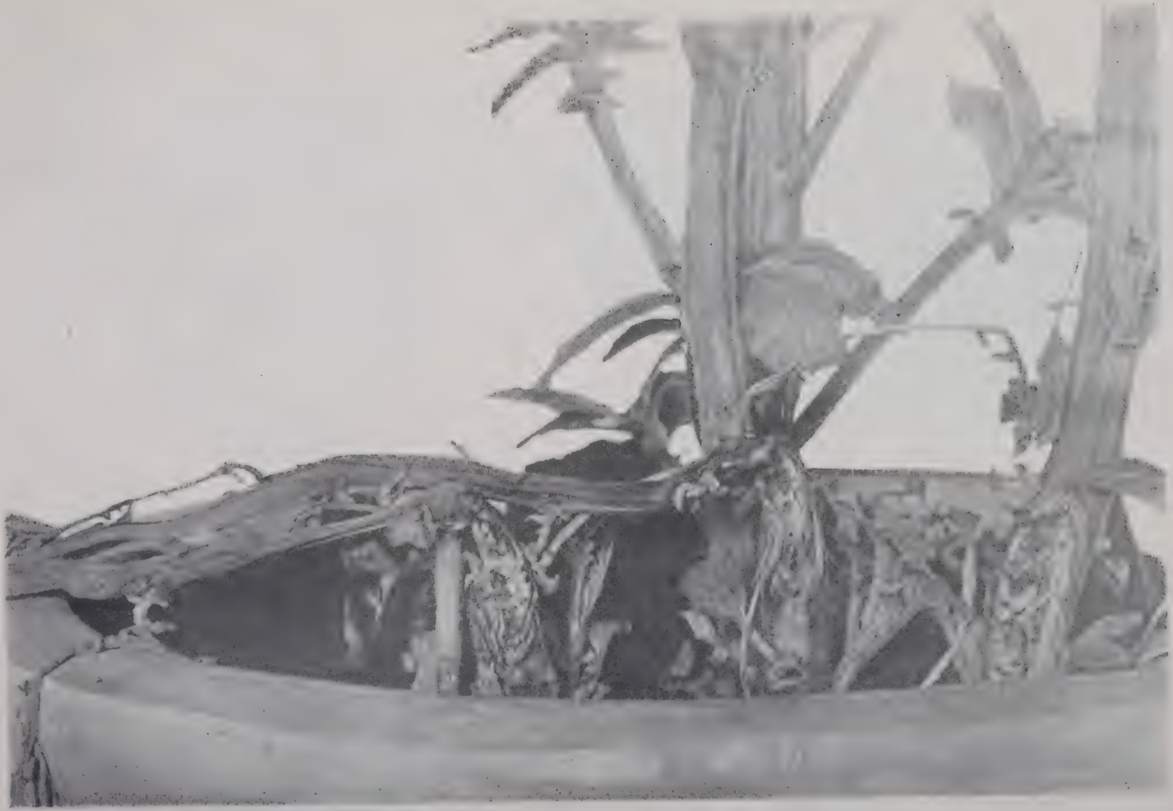

Plate XII. Inoculation of stems, near the surface of the ground. The fungus failed to make any growth in the stem until the two stems which had been cut deeply in the inoculation fell over and began to dry out. Photographed two weeks after inoculation.

PLATE XIII

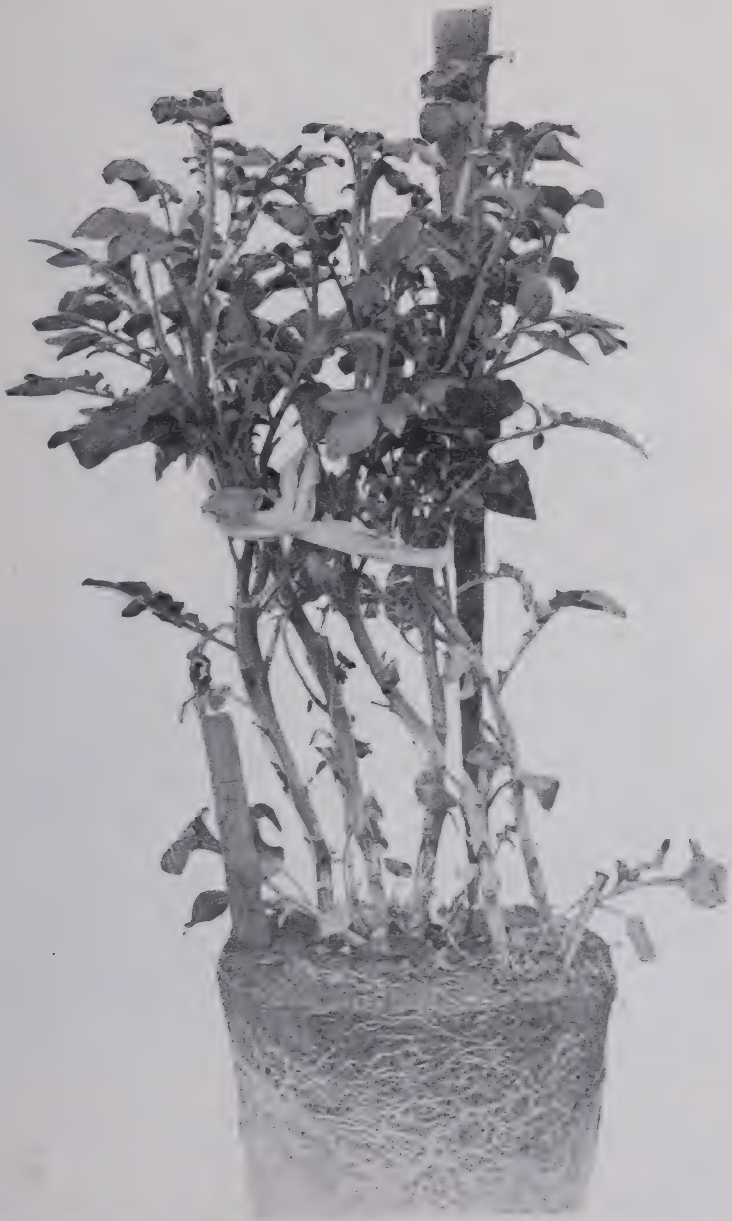

Plate XIII. Shows the appearance of the inoculated spots eight days after inoculation. The stems are quite normal and healthy in appearance.

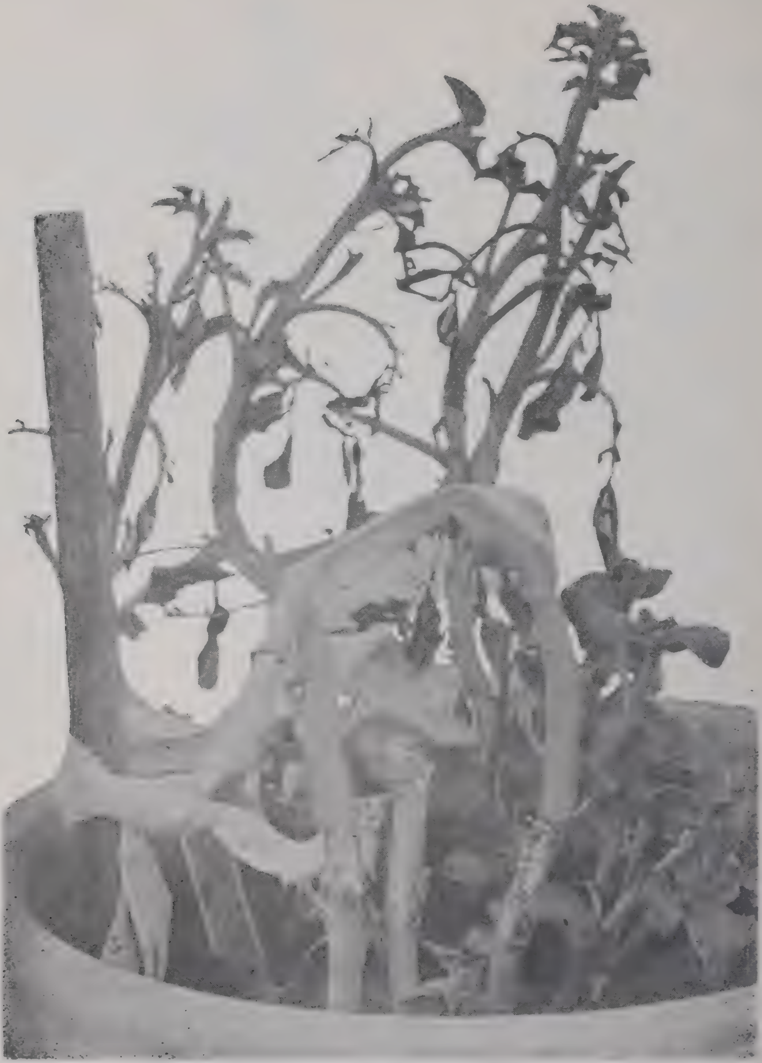

Plate XIV. Further inoculations of stems. One of these has broken over as a result of the inoculation wound without any extension of the fungus into the tissues of its stem. The drooping of the foliage here is due to the fact that this plant was accidently "nipped" by frost in moving it from the laboratory to the greenhouse. In spite of this frost injury these plants escaped infection and regained their normal appearance and vigor. Photographed two weeks after inoculation.

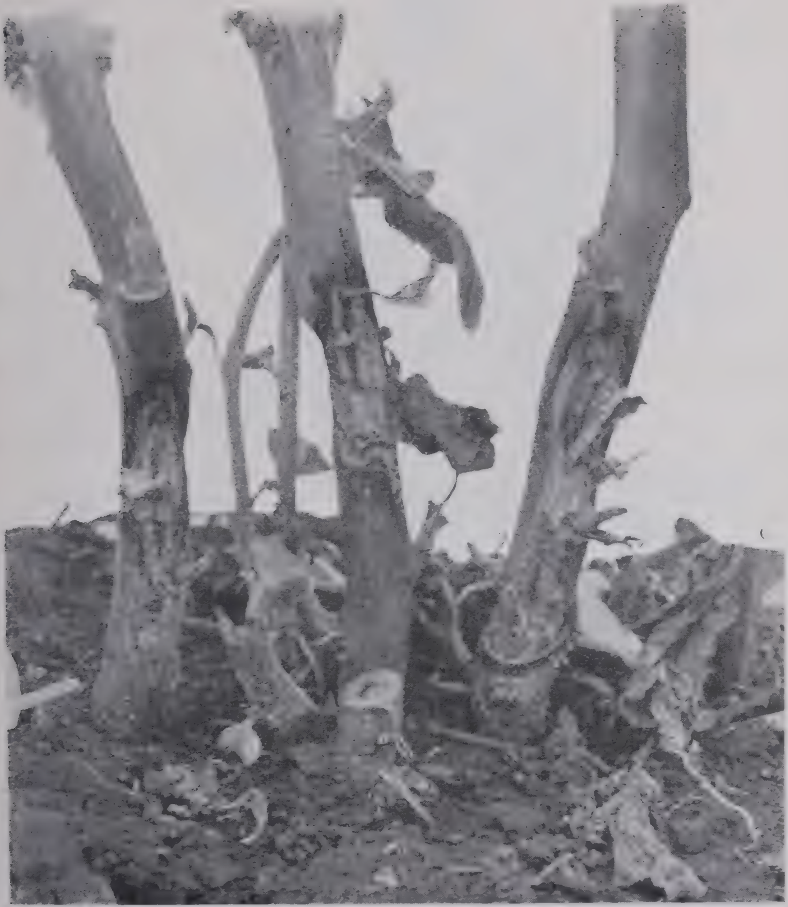

Plate XV. Inoculated stems. These wounds, after inoculation, were covered with moist cotton. In spite of this the fungus did not grow into the tissues of the stem but, as the result of cork formation, the inoculum was simply sloughed off. Photographed two weeks after inoculation.

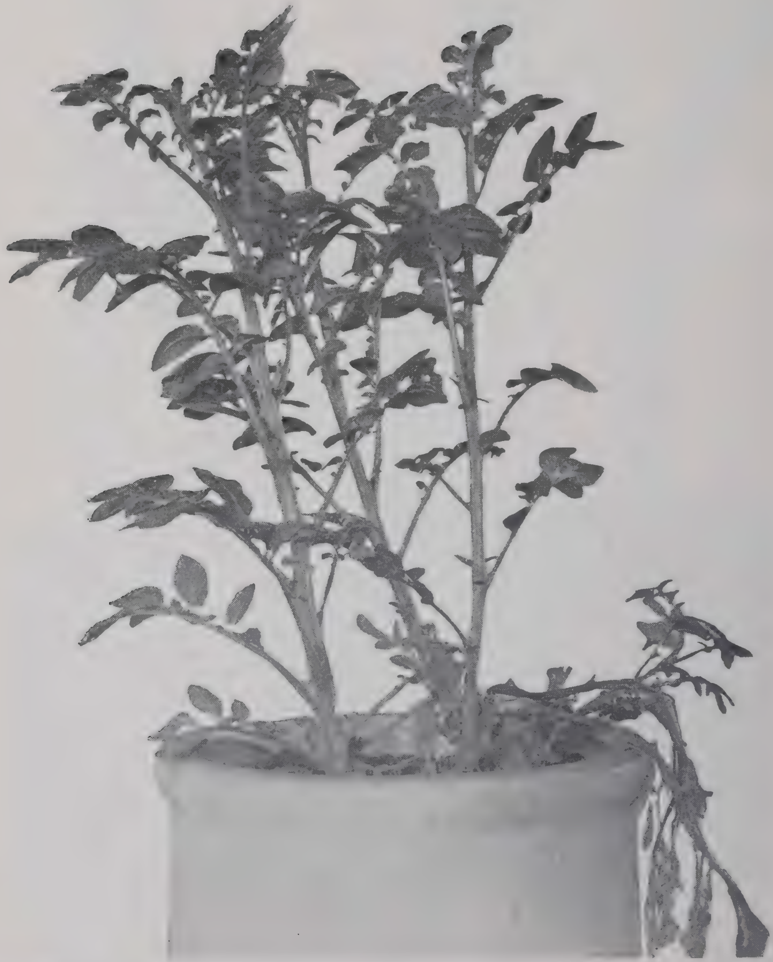

Plate XVI. The inoculated stems here have broken over as the result of the inoculation wound. In this partially dried condition of the stems they are attacked by this fungus. Photographed two weeks after inoculation.

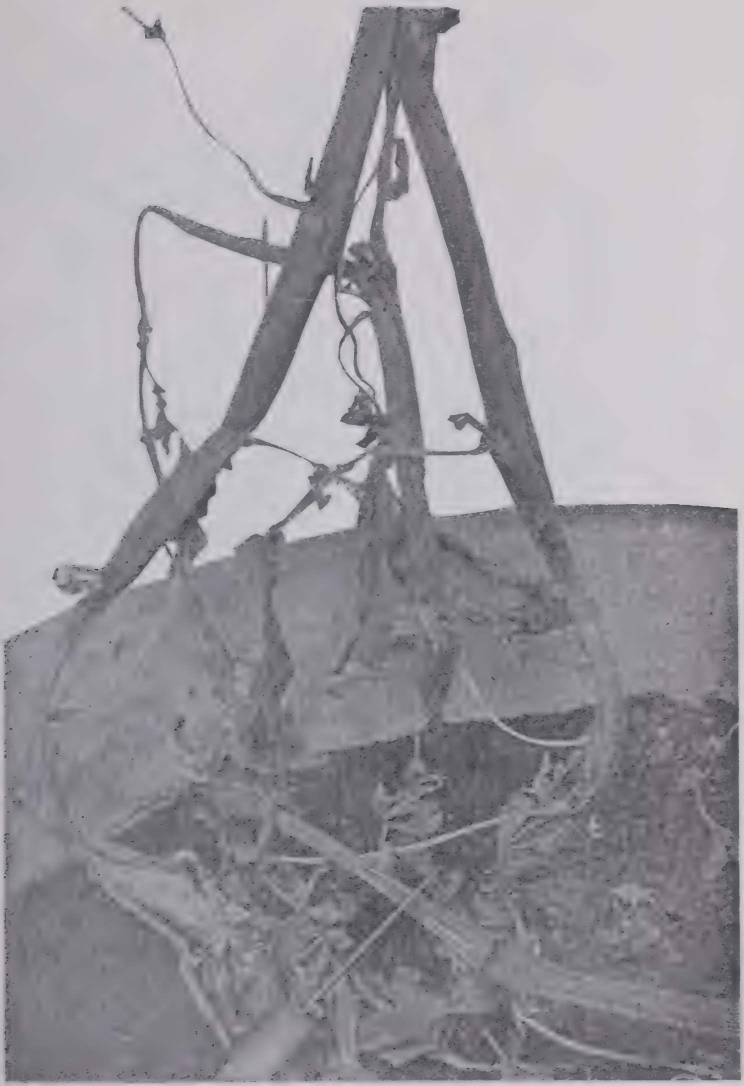

Plate XVII. In this case following inoculation the stem dried up so much about the wound that the upper part wilted. The fungus did not advance thru the dead parts into the subterranean organs of the plant. Photographed two weeks after inoculation.

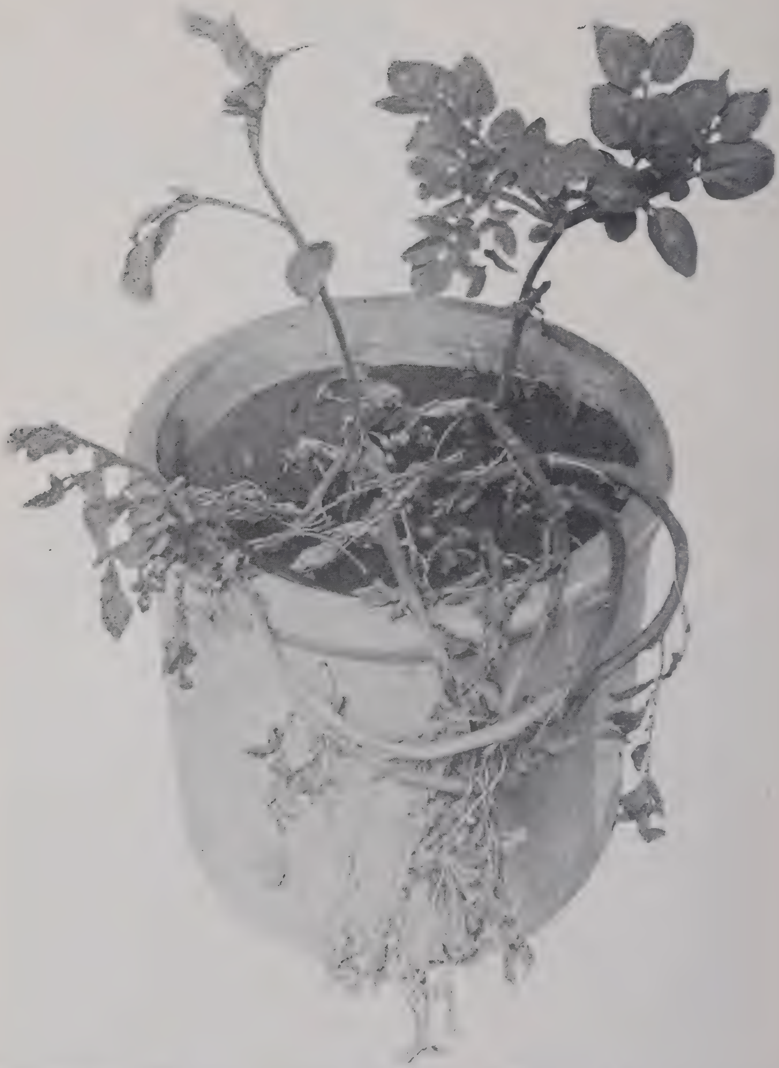

Plate XVIII. These inoculated stems have fallen over for the reason stated under Plate XVII. The fungus did not invade the stolons and tubers tho the subaerial stem had died. Photographed two weeks after inoculation.

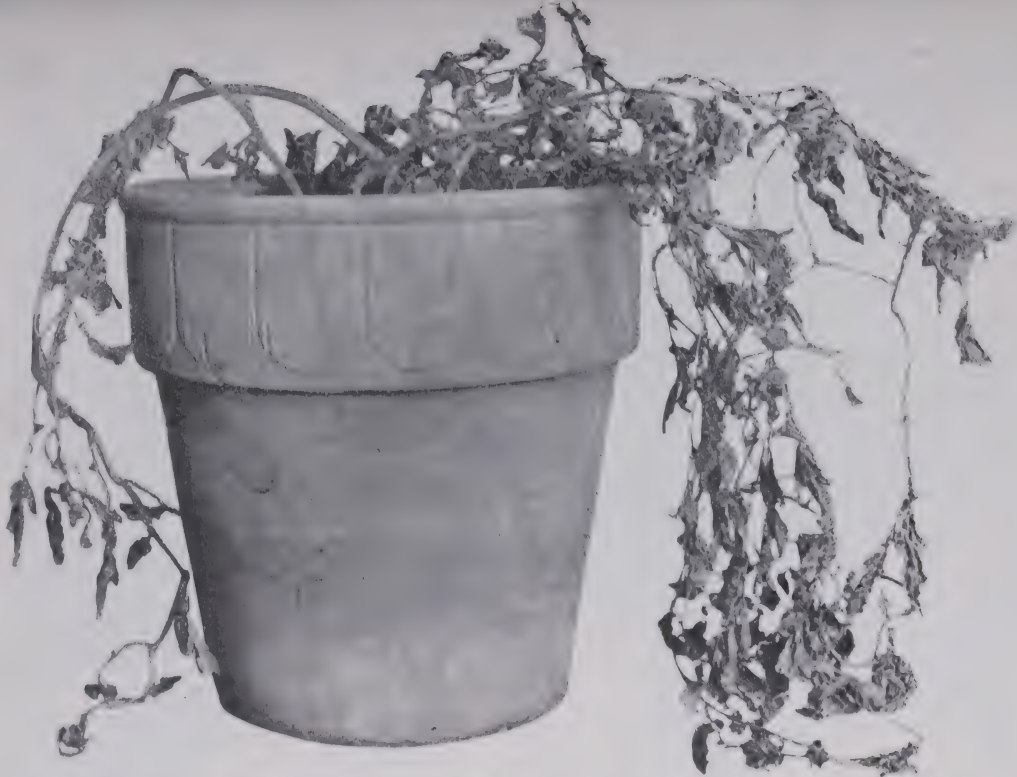

Plate XIX. The foliage after inoculation of the stems was severely attacked by thrips. In spite of this injury the fungus made no growth till the plant had died down and then the subterranean parts were not infected. Photographed six weeks after inoculation.

Plate XX. Shows the perfectly healthy foliage on stems eight days following the inoculation.

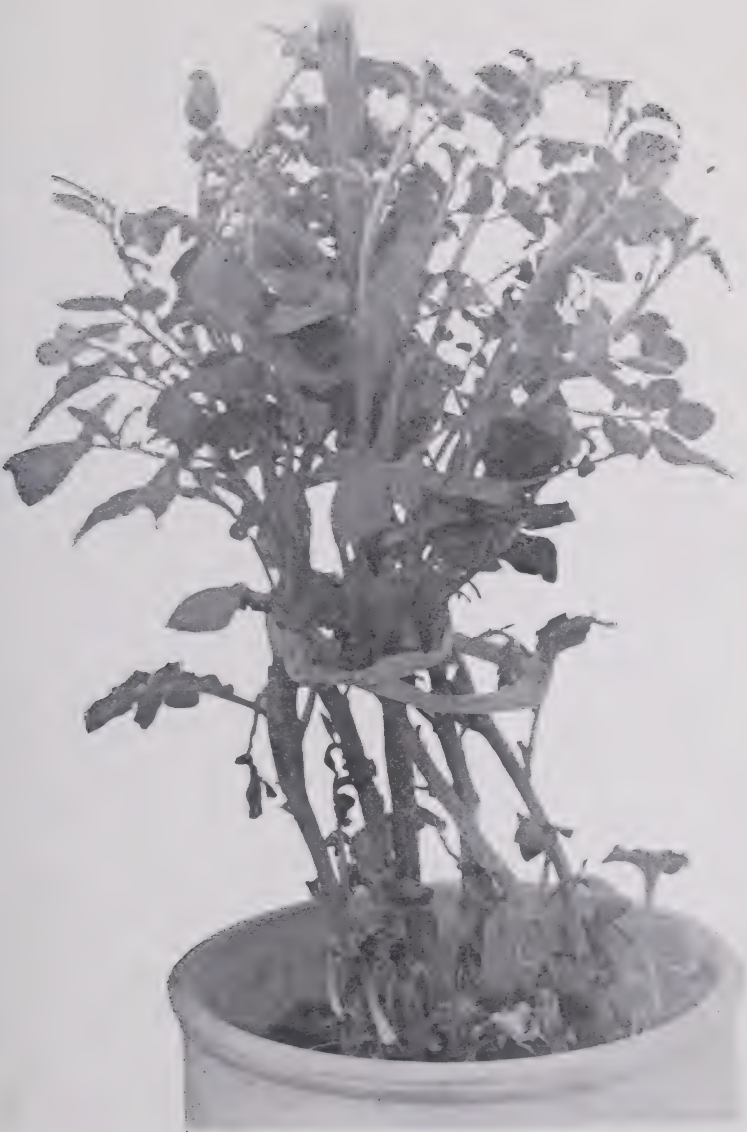

Plate XXI. Inoculated stems still showing, two weeks after inoculation, perfectly healthy foliage. The fungus had not extended into the tissues of the stem. The inoculum is being sloughed off thru the formation of wound cork.

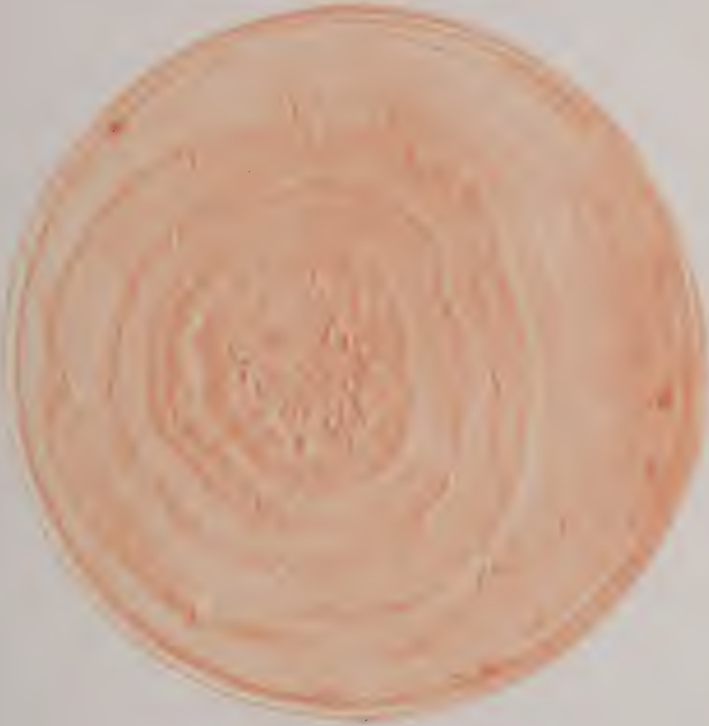

Plate XXII. A culture of *Fusarium tuberivorum* sp. n., showing its natural color and general appearance. This was grown in glucose agar and was two weeks old when photographed.

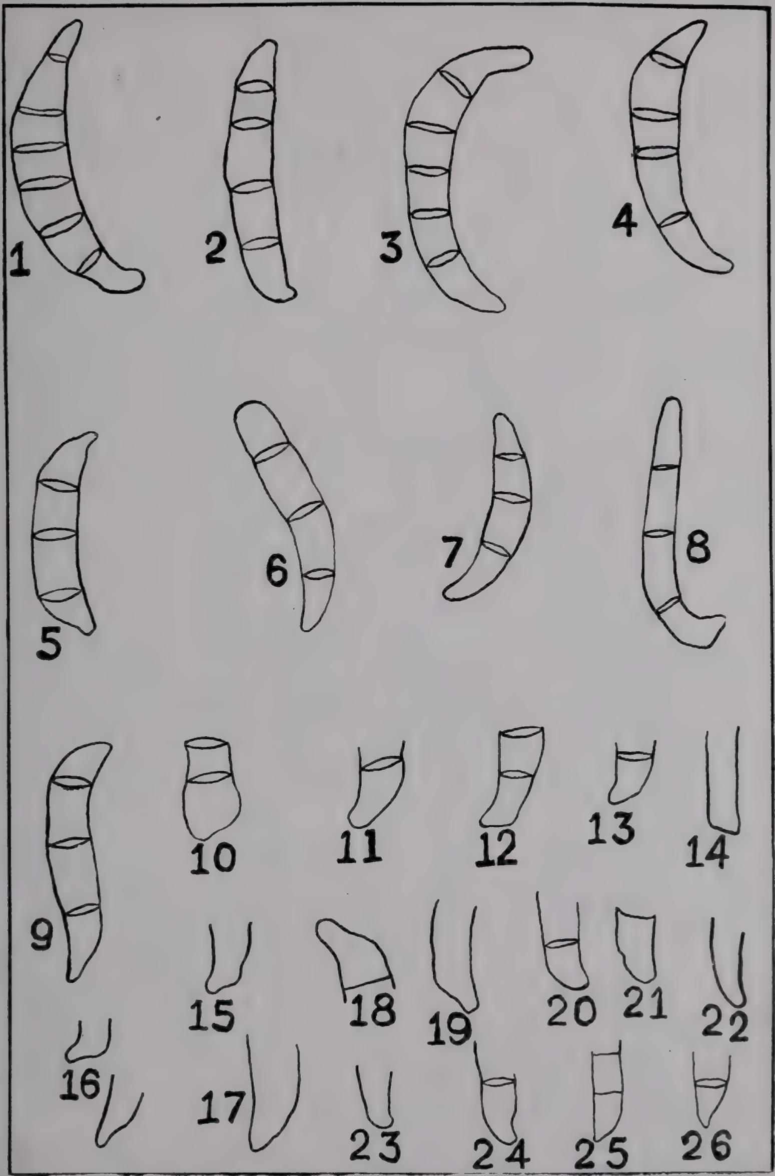

Plate XXIII. Figures 1 to 9 show spores from potato plug cultures, two weeks old, grown in the refrigerator at a temperature of 8° to 10° C. × 1000. Figures 10 to 17 and 19 to 26 show various degrees of development of the basal cell of spores from cultures on potato plugs, two weeks old, in a refrigerator at a temperature of 8° to 10° C. × 1000. Figure 18 shows the apical cell of a spore from the same culture as figures 10 to 17. × 1000.

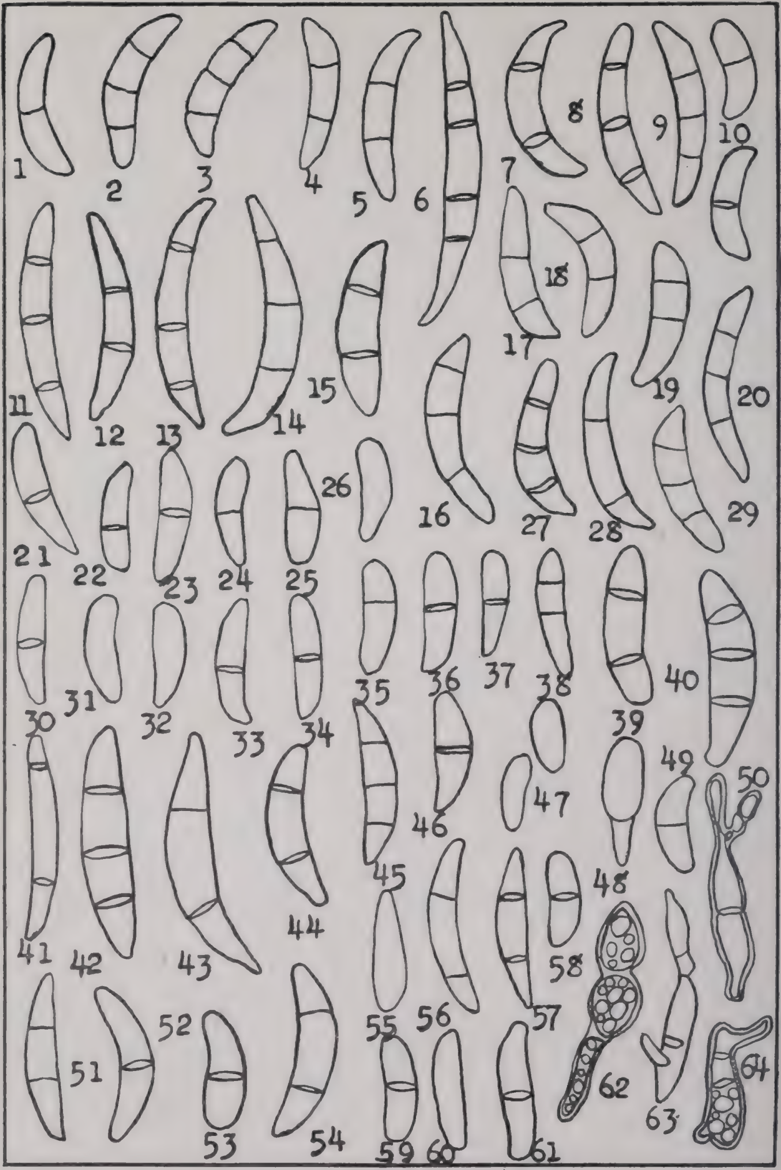

Plate XXIV. Figures 1 to 20 show spores from a potato plug culture, three weeks old. They are all descendants of a single 3-septate spore. × 1000. Figures 20 to 26, 30 to 38 show spores from raw potato culture two weeks old. × 1000. Figures 39 to 45 show spores from potato plug culture grown in diffuse light, three weeks old. × 1000. Figures 46 to 49, 53, 55 to 58, and 60 show spores from a potato selected at random. × 1000. Figures 50, 63 to 64 show spores from beef bouillon agar, fragmenting into oidia. One of these cells has germinated. × 1000.

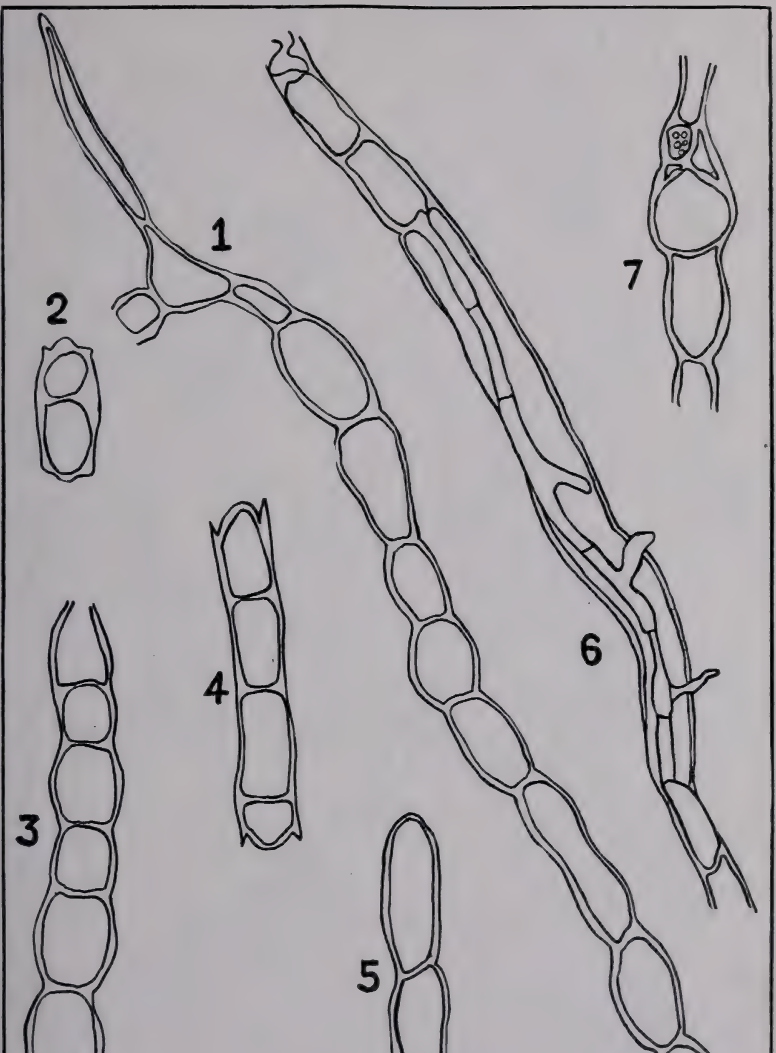

Plate XXV. Figure 1 shows a hypha from culture on beef bouillon agar. Figure 2 shows a spore-like fragment of the mycelium with the peculiar end structure. Figures 3 to 5 show hyphae from a culture on beef bouillon agar. Figure 6 shows the growth of a hypha into empty cells and its subsequent branching. All figures × 1000.

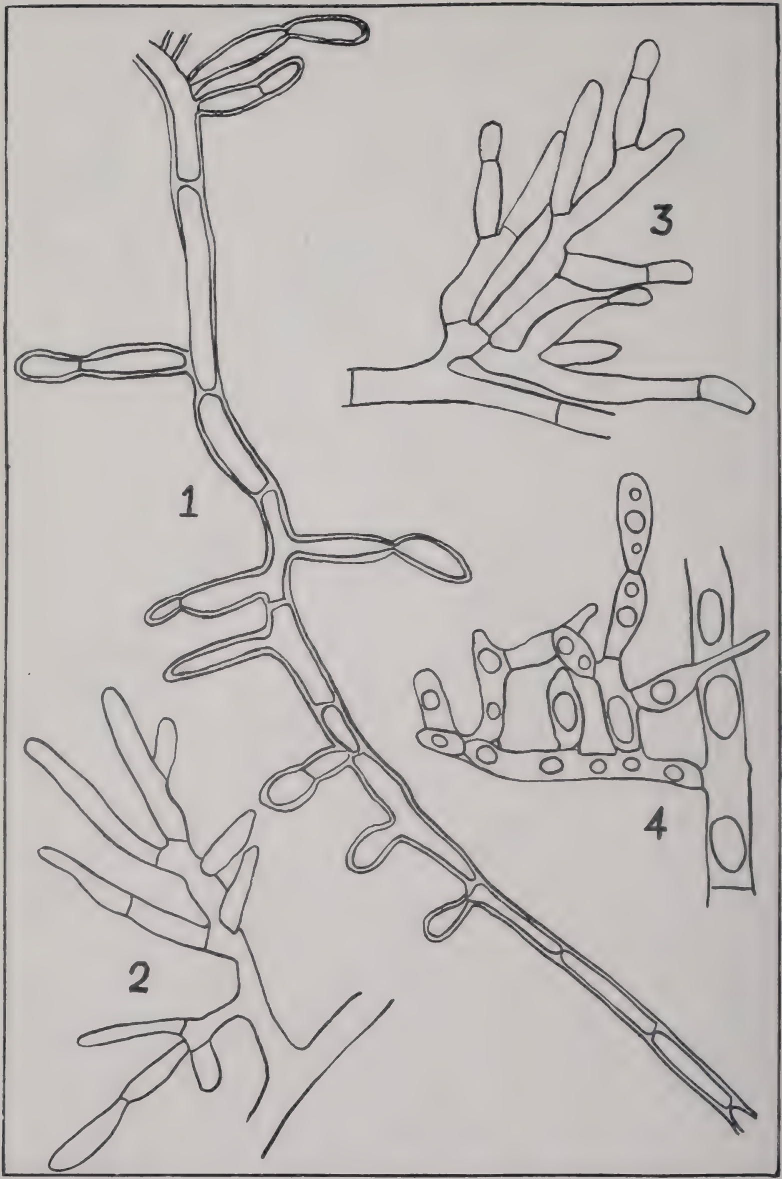

Plate XXVI. Figure 1 shows conidiophore from culture on potato plug. Figures 2, 3 are conidiophores from a dried out culture on potato stems. Figure 4 is a conidiophore from culture on potato plugs grown in the refrigerator. All figures × 1000.

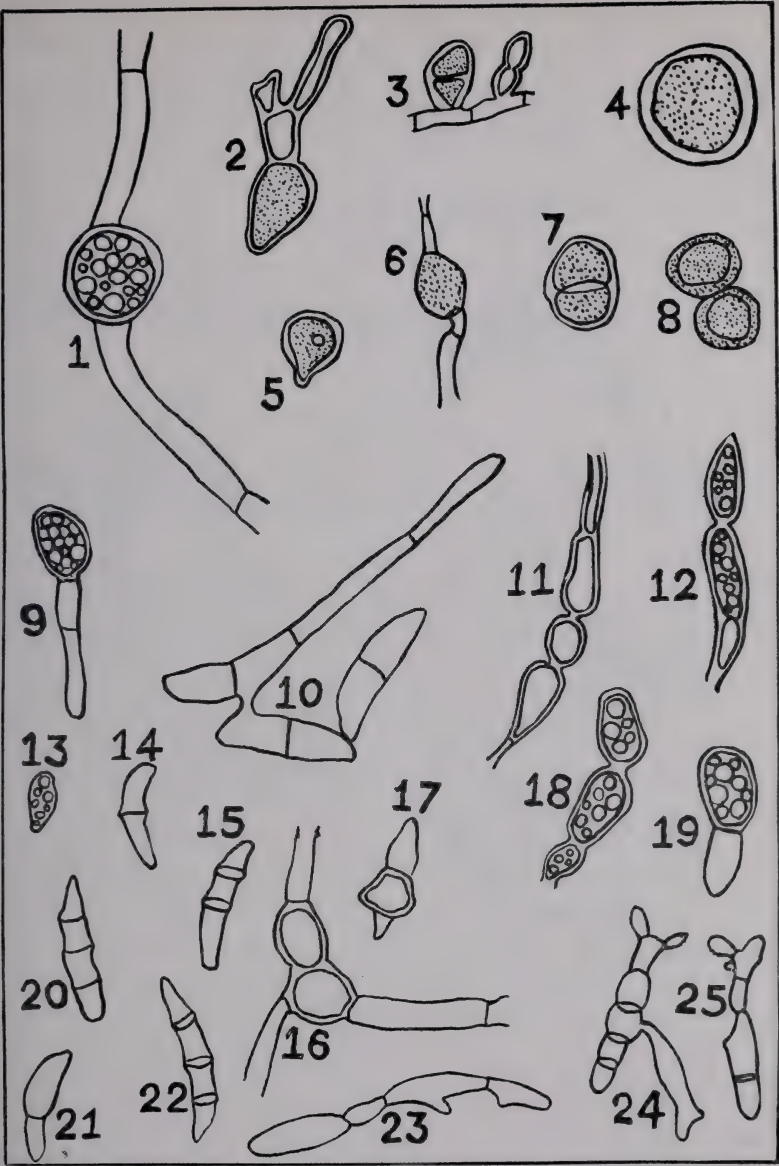

Plate XXVII. Figure 1. Chlamydospore from beef bouillon agar. Figures 2, 5, and 7 are chlamydospores from raw potato cultures. Figure 3 is a chlamydospore in water. Figure 6 is from same culture on potato. Figure 8 is a chlamydospore in water. Figure 9 is the terminal oidium from a potato plug culture. Figure 10 shows the fusion of conidia. Figures 11, 12, 18, 19 show the fragmentation of a germinating spore in distilled water. Figure 13 shows a spore from a water culture, eight weeks old. Figures 14, 15, 20, 22 show spores from raw potato plate culture, dry and 10 weeks old. Figures 16, 17 show the intercallary oidia. Figures 23 to 25 show germinating conidia. All figures × 1000.

PLATE XXVIII

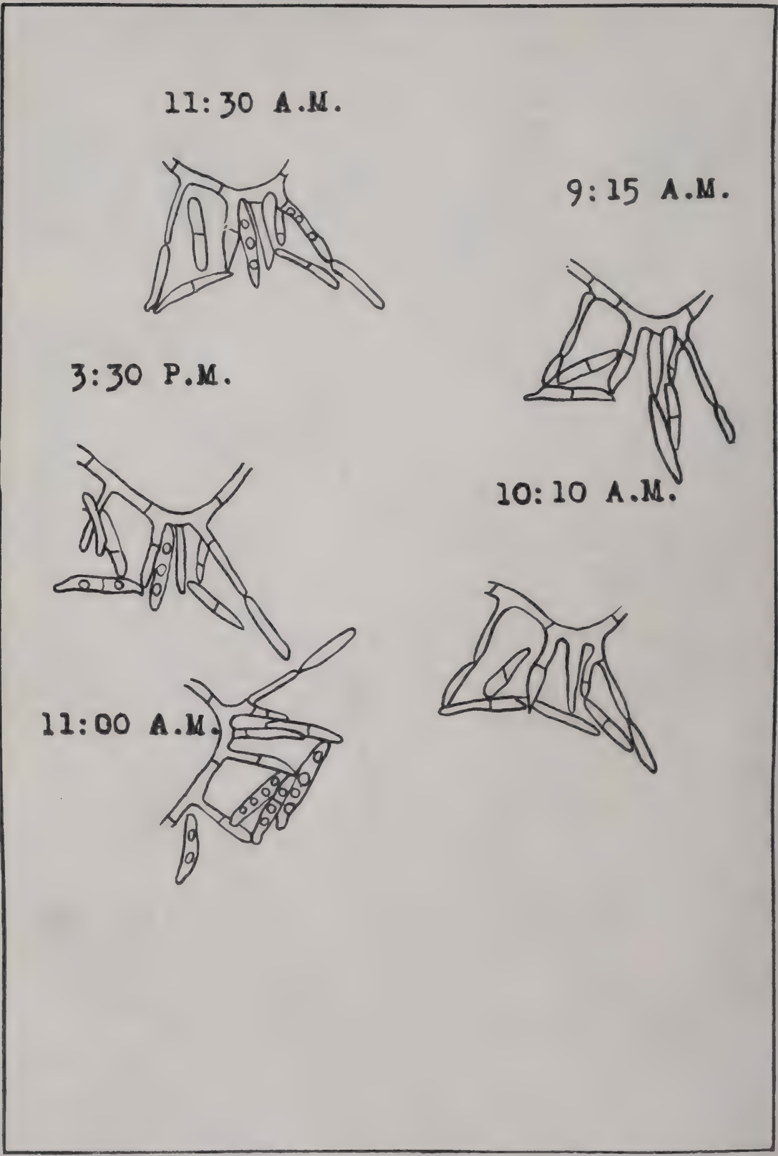

Plate XXVIII. Observations of conidiophores cutting off spores from 9:15 A. M., April 22, till 11 A. M., April 23. × 540.

RESEARCH BULLETIN NO. 2.

THE UNIVERSITY OF NEBRASKA.

BULLETIN
OF THE
AGRICULTURAL EXPERIMENT STATION
OF
NEBRASKA.

THE INHERITANCE OF QUANTITATIVE CHARACTERS IN MAIZE.

BY COLLABORATION OF
R. A. EMERSON,
THE UNIVERSITY OF NEBRASKA,
AND
E. M. EAST,
BUSSEY INSTITUTION OF HARVARD UNIVERSITY.

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CONTENTS.

PAGE

Introduction 5

The theory of multiple factors affecting a single character complex 8

Methods and materials used 27

Inheritance of—

- Number of rows per ear 29
- Length of ears 40
- Diameter of ears 54
- Weight of seeds 57
- Breadth of seeds 61
- Height of plants 64
- Number of nodes per stalk 79
- Internode length 82
- Number of stalks per plant 87
- Total length of stalks per plant 93
- Duration of growth 96

Summary and general conclusions 103

Manipulation of quantitative characters in plant breeding 110

Literature cited 118

THE INHERITANCE OF QUANTITATIVE CHARACTERS IN MAIZE.

BY COLLABORATION OF R. A. EMERSON AND E. M. EAST.*

INTRODUCTION.

When Mendel's law of heredity was rediscovered by Correns, de Vries, and von Tschermak, most biologists were justly skeptical of the possibility that it might be general in scope. The early disclosure that a wide range of breeding facts in both the animal and the vegetable kingdom were made orderly and consistent by using the Mendelian notation† brought about only a slight change in this attitude. A few optimistic minds believed that the similarity of the breeding phenomena in animals and in plants indicated that the Mendelian mechanism was intimately associated with that fundamental process common to both kingdoms,—sexual reproduction. Those who reasoned in this manner suspected a broad general operation of the law of segregation and recombination of unit factors. The remaining great majority held to their position of respectful distrust.

There were several reasons for this situation. A goodly portion of the responsibility for it rests upon de Vries, who, from data of doubtful significance, drew the broad conclusion that varietal characters and specific characters obey quite different laws of heredity. Unpaired or unisexual characters he believed to have sole claim to the rank of specific differences. These characters, he thought, are incapable of Mendelian segregation. Segregating characters he called paired or bisexual qualities, and these he believed worthy of only varietal rank. The fallacy in de Vries' reasoning is obvious, now that Bateson's presence and

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* Harvard University, Bussey Institution, Jamaica Plain, Mass.

† The prevailing Mendelian terminology is followed in this paper, but it must not be assumed that the writers regard Mendelian formulæ as other than a helpful descriptive shorthand convenient for describing breeding facts. Hypothetical germ cell factors are substituted for somatic characters because they are useful in exactly the same manner that hypothetical formulæ are useful in describing chemical reactions. To establish the contention that quantitative characters are essentially Mendelian in their inheritance, therefore, it is only necessary to show that the notation adequately describes the breeding facts.

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absence notation has come into general use. In truth one must accept a reversal of de Vries' views, for the presence and absence notation is based on the fact that the hereditary transmission of a factor can only be determined when the factor is present in one of the parental gametes and absent from the other.

A second reason for limiting the operation of Mendel's law was the earlier misconception of the importance of the phenomenon of dominance. This reason shortly disappeared when it was found that perfect dominance was the exception rather than the rule and that cases where dominance was entirely lacking were frequently found.

These were important concessions that contributed much toward recognition of the importance of the Mendelian conception of heredity, but the main stumbling-block to Mendelism lay in the comparative frequency of quantitative variations. The variations whose behavior in crosses yielded to a simple factorial interpretation were all qualitative in character. They could reasonably be regarded as being due to the presence or absence of something in the gamete. Such varietal differences existed by the score, yet their number was insignificant when compared with the multitude of variations expressed as differences in size of organs common to the individuals under consideration. Many of these differences, it is true, were fluctuations due to environment which were non-heritable,* but the remaining transmissible variations were legion. About three years ago, however, a hypothesis was proposed which would bring even this broad category of facts under the scope of the law of unit-factor segregation and recombination. The experimental data upon which this hypothesis was then based and the data that have been collected subsequently are comparatively few, yet the fact that the experiments of several independent investigators have been corroborative in every detail makes it plausible to believe that its main contention will soon be established beyond a reasonable doubt.

If this statement be granted for the moment, one might hazard the suggestion that the probable limits that circumscribe Mendelian phenomena really do coincide with the limits within which transmissible character potentialities are transferred by typical sexual reproduction. In other words, Mendelian phenomena are in some way bound up in and coincident with that preparation of the reproductive cells called maturation and their subsequent fusion to form a new organism. This, it is thought, is an admissible induction from the conspicuous diversity and profusion of Mendelian phenomena, and from the fact that the only indisputable cases of non-mendelizing characters are (1) that discovered by Correns in *Mirabilis jalapa,* where a pathological condition affecting a leaf function is carried by the cytoplasm and inherited only thru the mother, and (2) that reported by Baur for *Pelargonium zonale,* in which vegetative segregates (sectorial chimeras) occur in F_1 plants and breed true in F_2.

---

* It has been shown that if adaptive responses are ever heritable, the phenomenon is so rare that it may be neglected in experimental pedigree cultures.

The acceptance of this point of view depends largely upon whether a correct interpretation of the inheritance of quantitative variations has been reached. The authors, therefore, desire to submit a somewhat complete discussion of the inheritance of this category of variations, supported by data from experiments on maize that have been gathered independently. If there be criticism that the conclusions drawn are too broad since the facts have been gathered from a single plant species, the authors may answer that each has made corroborative investigations upon other species which they expect to publish in the near future.

The experiments conducted by one of the writers were begun at the Connecticut Agricultural Experiment Station at New Haven in 1906 and removed to the Bussey Institution of Harvard University at Forest Hills, Massachusetts, in 1909. The materials employed in this study consisted principally of crosses of Tom Thumb pop with Black Mexican sweet and of Watson flint with Leaming dent. The number of rows per ear were noted in several other crosses, the parents of which are listed later in this paper. For help in gathering and compiling the data from these crosses, we are indebted to H. K. Hayes, plant breeder of the Connecticut Agricultural Experiment Station, and to O. E. White and D. L. Davis, graduate students in genetics at Harvard University.

The experiments of the other writer were begun at the Nebraska Agricultural Experiment Station at Lincoln in 1908, where they have been continued to the present time. A part of the material studied in 1911 was grown at the Bussey Institution at Forest Hills, Massachusetts. The plants used in this study were crosses of Tom Thumb pop with Missouri dent and of the latter variety with California pop. For assistance in connection with this work, we acknowledge our indebtedness to R. F. Howard, now assistant horticulturist of the Wisconsin Agricultural Experiment Station, to F. C. Miles, graduate student in genetics at the University of Nebraska, to E. H. Herminghaus, student assistant, and particularly to E. R. Ewing, who has computed most of the statistical constants from the data obtained from the Nebraska experiments.

THE THEORY OF MULTIPLE FACTORS AFFECTING A SINGLE CHARACTER COMPLEX.

Bateson and later other writers have shown that development of qualitative characters may depend upon the interaction of two or more gametic factors that are transmitted independently. When one of these essential factors is absent from the zygote the visible character does not develop. Thus color in the sweet pea, in stocks, in snapdragons, in primulas, in beans, and in the hair of various animals does not develop unless a basic factor, generally known as the color factor *C*, is present in addition to the color determiner which fixes the shade of the color. When either the color factor or the specific determiner is absent, color does not develop.

In two papers published in 1908 and 1909, Nilsson-Ehle showed that certain colors in wheat and in oats are determined not by single gametic factors but by several, the presence of any one of which serves to determine the color. In other words, these gametic factors, altho affecting the same zygotic character, are not allelomorphic to each other, but to their own absence. Nilsson-Ehle in 1908 showed how such facts gave a foundation for a theory interpreting the inheritance of *quantitative* characters, altho no experimental data were submitted to support the hypothesis.

A little later, East, in ignorance of Nilsson-Ehle's 1908 paper,* submitted a similar case of color inheritance in maize, and developed a similar theory.

Fortunately this type of inheritance was discovered in characters showing dominance, otherwise its proof would have been very difficult. We will describe these cases first, and afterwards show their bearing on the so-called "blending" inheritance characteristic of quantitative characters.

Nilsson-Ehle (1909) crossed together many varieties of oats differing in glume color. The results from all but one of these crosses were quite simple. Presence of color dominated absence. Where the parents differed in one character pair, such as black *(B)* and absence of black *(b)*, the ratio in F_2 was 3 : 1. Where the parents differed in two allelomorphic pairs, black *(B)* and absence of black *(b)*, and gray *(G)* and absence of gray *(g)*, the ratio in F_2 was 12 black : 3 gray : 1 white, because the classes *BG* and *Bg* could not be distinguished. So far there were no complications. In one of these crosses between a black glumed and a white glumed race, however, the F_2 generation was 630 black : 40 white, clearly a ratio of 15 black : 1 white. Here there appeared to be two factors for black, each dominant to its own absence, segregating and recombining independently. The zygotic formula of the black race may be expressed as $B_1B_1B_2B_2$ and that of the white race as $b_1b_1b_2b_2$. The F_1 generation brings both of these factors to the heterozygous condition, $B_1b_1B_2b_2$, and in F_2 gives $9B_1B_2 : 3B_1b_2 : 3b_1B_2 : 1b_1b_2$. But as the first three classes are alike in appearance, the ratio of F_2 is 15 black : 1 white.

---

* East learned of Nilsson-Ehle's second paper, which does not give the full development of the quantitative-inheritance theory, after the first draft of his own paper was written, but Nilsson-Ehle deserves full credit for the theory that is based upon his beautiful results on qualitative characters.

Again, experimenting with wheat, Nilsson-Ehle found a dihybrid Mendelian ratio. A brown headed wheat crossed with a white headed variety gave in F_2 1410 brown headed plants to 94 white headed plants, a ratio exactly 15 : 1. There is hardly a doubt that the brown headed variety had the formula $B_1B_1B_2B_2$ and the white headed variety the formula $b_1b_1b_2b_2$. The proof of the interpretation comes from a more surprising experiment of the same investigator.

He made six crosses between a red-seeded wheat and a white-seeded variety. The F_1 plants were all red-seeded: *the 384 plants of the F_2 generation were also red-seeded.* This result was so peculiar that selfed seed of all of the 78 F_2 plants of one cross were grown and the progeny of each recorded in the F_3 generation. This result was obtained:

50 F_2 plants gave only red-seeded plants.
8 F_2 plants gave approximately 3 red : 1 white plants.
15 F_2 plants gave approximately 15 red : 1 white plants.
5 F_2 plants gave approximately 63 red : 1 white plants.

The interpretation of this result was that a trihybrid had been produced by crossing $R_1R_1R_2R_2R_3R_3$ with $r_1r_1r_2r_2r_3r_3$, each R factor being able to produce the red color in the seed, but segregating with its own absence independently of the other factors. The red F_1 generation would have the formula $R_1r_1R_2r_2R_3r_3$ and should by recombination produce 63 red : 1 white plants in F_2. To be sure, no white-seeded plants were obtained in the 384 individuals forming the total F_2 generation, but such a result might be expected frequently in chance matings of this type following the Law of Error, unless more F_2 progeny were grown. The real proof of the interpretation comes from the F_3 generation as noted before. The F_2 generation, theoretically, consists of 63 reds to 1 white. The 63 red plants, tho similar in appearance, should have the different zygotic formulae expected of an ordinary trihybrid, and therefore should give different results in F_3 as follows:

	F_2	gives in	F_3
Class 1.	1 $R_1R_1R_2R_2R_3R_3$		red only.
Class 2.	2 $R_1r_1R_2R_2R_3R_3$		red only.
Class 3.	2 $R_1R_1R_2r_2R_3R_3$		red only.
Class 4.	2 $R_1R_1R_2R_2R_3r_3$		red only.
Class 5.	4 $R_1r_1R_2r_2R_3R_3$		red only.
Class 6.	4 $R_1R_1R_2r_2R_3r_3$		red only.
Class 7.	4 $R_1r_1R_2R_2R_3r_3$		red only.
Class 8.	8 $R_1r_1R_2r_2R_3r_3$		63 red : 1 white.
Class 9.	1 $R_1R_1R_2R_2r_3r_3$		red only.
Class 10.	2 $R_1r_1R_2R_2r_3r_3$		red only.
Class 11.	2 $R_1R_1R_2r_2r_3r_3$		red only.
Class 12.	4 $R_1r_1R_2r_2r_3r_3$		15 red : 1 white.
Class 13.	1 $r_1r_1R_2R_2R_3R_3$		red only.
Class 14.	2 $r_1r_1R_2r_2R_3R_3$		red only.
Class 15.	2 $r_1r_1R_2R_2R_3r_3$		red only.
Class 16.	4 $r_1r_1R_2r_2R_3r_3$		15 red : 1 white.
Class 17.	1 $R_1R_1r_2r_2R_3R_3$		red only.
Class 18.	2 $R_1r_1r_2r_2R_3R_3$		red only.
Class 19.	2 $R_1R_1r_2r_2R_3r_3$		red only.
Class 20.	4 $R_1r_1r_2r_2R_3r_3$		15 red : 1 white.
Class 21.	1 $R_1R_1r_2r_2r_3r_3$		red only.
Class 22.	2 $R_1r_1r_2r_2r_3r_3$		3 red : 1 white.
Class 23.	1 $r_1r_1R_2R_2r_3r_3$		red only.
Class 24.	2 $r_1r_1R_2r_2r_3r_3$		3 red : 1 white.
Class 25.	1 $r_1r_1r_2r_2R_3R_3$		red only.
Class 26.	2 $r_1r_1r_2r_2R_3r_3$		3 red : 1 white.

Collecting the statistics, we find that the 63 red plants of the trihybrid minimum of 64 in F_2 should give in F_3, when selfed, 37 breeding true to red, 6 throwing reds and whites in the ratio of 3:1, 12 throwing reds and whites in the ratio of 15:1, and 8 throwing reds and whites in the ratio of 63:1. From these data one can calculate the most probable result in the experiment where 78 plants were followed to the F_3 generation. It is as follows:

Type	Per cent	Actual result	Most probable expectancy
Plants breeding true to red	58.8	50	46
Plants giving 3 red : 1 white.........	9.5	8	7
Plants giving 15 red : 1 white.........	19.0	15	15
Plants giving 63 red : 1 white........	12.7	5	10

The actual results are so close to those expected on the theory that it would be a most wonderful coincidence if the theory were not correct.

The original basis for the theory developed by East (1910) was of this same character. Two factors for the production of yellow color in the endosperm of maize were found. The presence of either factor produced yellow seeds identical in appearance, but each was allelomorphic to its own absence in crosses. An ear with the zygotic formula Y_1Y_1 was exactly like an ear with the zygotic formula Y_2Y_2. It is true that there was a cumulative effect so that ears with the zygotic formula $Y_1Y_1Y_2Y_2$ were darker in color than those homozygous for a single factor, but those zygotes homozygous for either single factor were indistinguishable. A zygote from any cross which produced the constitution $Y_1y_1Y_2y_2$ gave approximately 15 yellows: 1 white in the next generation when selfed. A total of 5,222 segregates were recorded, of which 4,880 were yellow and 342 white. This ratio is very nearly 15:1, the closest possible ratio being 4,895: 327. The actual results were therefore astonishingly close to theoretical expectation.

These segregates were followed to the F_3 generation, and gave decisive evidence that they varied in zygotic constitution in accordance with the scheme which has just been outlined. Theoretically the 15 yellows of F_2 should have the following zygotic formulae:

	F_2	gives in	F_3
9	1 $Y_1Y_1Y_2Y_2$		all yellow.
	2 $Y_1Y_1Y_2y_2$		all yellow.
	2 $Y_1y_1Y_2Y_2$		all yellow.
	4 $Y_1y_1Y_2y_2$		15 yellow : 1 white.
3	1 $Y_1Y_1y_2y_2$		all yellow.
	2 $Y_1y_1y_2y_2$		3 yellow : 1 white.
3	1 $y_1y_1Y_2Y_2$		all yellow.
	2 $y_1y_1Y_2y_2$		3 yellow : 1 white.

Each of these classes provided for by the theory were actually obtained. Those ears having the formula $Y_1Y_1y_2y_2$ were indistinguishable from those ears having the formula $y_1y_1Y_2Y_2$, but where Y_1Y_1 and Y_2Y_2 were both present in the same zygote the seeds were a much darker yellow than where either yellow alone was present.

It should be noted that Emerson (1911) has found two yellow colors in the endosperm of maize that seem to be unlike in appearance. One is a golden yellow and one a light yellow. It is possible that further observations will show that the orange yellow is due to the cumulative action of two similar or identical yellows as described above, but it is also possible that action of a hitherto unobserved *intensity* factor is responsible for the phenomenon.

East and Hayes (1911) reported one other case of this kind where dominance is comparatively complete. Two varieties of maize breeding true to that form of red pericarp which comes to complete development only in sunlight were crossed. The F_2 generation, instead of breeding true to this color as was expected, gave a fraternity composed of ears with and without the red pericarp in the ratio of 15:1. The extracted recessives bred true, but no further observations were made on the segregates having red ears. It can hardly be doubted, nevertheless, that here again were two factors producing apparently the same visible character, each segregating from its own absence and not allelomorphic to each other.

Let us now consider what peculiarities such a scheme of inheritance presents as a whole. If there is absolute dominance and each dominant unit factor affects the zygote as fully as all do when combined, it would take but a few character pairs to present the appearance of breeding true in F_2. This we saw to be the case in the wheats. The F_2 generation of 384 plants appeared to show no segregation. Ordinarily six pure recessives might be expected from this number of plants when dealing with three interacting factors in a heterozygous condition, but if four units $A_1A_2A_3A_4$ were crossed with their absence $a_1a_2a_3a_4$, only one pure recessive could reasonably be expected out of 256 F_2 zygotes and in the numbers generally reported from pedigree cultures they would often be lacking. This sort of occurrence may explain the classical (for some unknown reason, because uncorroborated) strawberry crosses of Millardet (1894) where the F_1 generation is supposed to have resembled the male parent and bred true. A striking character in the male parent due to four or five allelomorphic pairs showing perfect dominance would appear to give such a result. One should be careful, at least, about reporting heterozygotes as breeding true without sufficient evidence.

Another important class of facts resting on this theoretical basis may be illustrated by the case of the red pericarps in maize that has just been described. Two maize varieties, both breeding true for this peculiar pericarp red that develops only in a certain amount of light, were crossed. The F_1 plants, when selfed, unexpectedly gave one plant with colorless pericarp on the ears out of every sixteen. Now one of these varieties had been crossed previously with a white variety and had given the usual monohybrid ratio of 3 : 1 in F_2. This character was therefore represented by the presence of a single factor R and behaved as it should when it met its absence r. But since the cross between the two red varieties gave the dihybrid ratio in F_2, one must suppose that, tho alike in appearance, they were not allelomorphic to each other. One was $R_1R_1r_2r_2$ and the other $r_1r_1R_2R_2$. Each bred true to red within its variety, but when crossed, each factor met its absence and an F_1 was produced heterozygous in both. The resulting F_2 generation for this reason was exactly the same as if a red $R_1R_1R_2R_2$ had been crossed with a white $r_1r_1r_2r_2$.

Just imagine such a case when more pairs of factors are in action. If units $A_1A_2A_3a_4$ met units $a_1a_2a_3A_4$ in hybridization, there is again the apparent paradox of two individuals which have bred true for a particular character, giving pure recessives in F_2 when crossed. But this time the zygote without the character occurs only once in 256 progeny. When one considers the rarity with which dominants or recessives pure for all factors are obtained when three factors or more interact, he can hardly avoid the suspicion that here is a perfectly logical way of accounting for many cases of so-called atavism that are not explained by the interaction of two dominant factors. No definite cases can be pointed out, but it is not uncommon for a florist to have a new type appear with regularity tho with extreme rarity for many generations after a cross. No doubt proper analyses of controlled cultures would elicit simpler explanations of most of these cases, but some of them surely must be referred to the class of phenomena we have just discussed. It is quite within the range of possibility that some of de Vries' Oenothera mutants have originated in this manner.

The colored zygotes, in the glume color of oats and head color and seed color of wheat investigated by Nilsson-Ehle, have been treated as if they were exactly alike in appearance. This was not always the case. The color produced by additional factors was often somewhat cumulative, particularly so in the case of the colored wheat heads. Where the two dominant factors were present there was usually more color developed than where only one was present. The classes could not be distinguished visually, but the general tendency was cumulative. This fact is nicely illustrated by the F_2 segregates of the maize cross in which yellow endosperm behaved as a dihybrid. All of the classes having different gametic constitutions vary in the intensity of their yellow color. The yellow becomes lighter in shade in the following order: $Y_1Y_1Y_2Y_2$, $y_1y_1Y_2Y_2$ or $Y_1Y_1Y_2y_2$, Y_1y_1 or Y_2y_2, and $Y_1y_1Y_2y_2$.

These facts open up two new and important phases of Mendelian inheritance. The first is the possibility of having new characters formed under operation of the Mendelian law. The matter is purely speculative, nevertheless it is suggestive. We do not know why two factors should exist that apparently cause identical characters to be formed in the same plant organ, but different factor-carrying apparatus of some kind which makes possible independent segregation and recombination in the germ cells is indicated. If one accepts—for the sake of argument only—the idea that Mendelian factors are expressions of chromosome functions (Emerson 1911a), then the location of any factor *A* in chromosome number one would give a monohybrid ratio when paired with a homologous chromosome in which *A* was absent, the location of the same factor in both chromosomes 1 and 2 would give the dihybrid ratio when paired with chromosomes in both of which *A* was absent, and so on to the limit of the gametic number of chromosomes. Now if in any line of descent a factor *X* should become located in different chromosomes or in any other way be so affected as not to be allelomorphic to itself in *all* combinations, and further if additional expressions of the factor should result in a cumulative effect, one might have new quantitative characters or even apparently new qualitative characters formed. This hypothesis we consider very important as it gives the first reasonable explanation of the production of new characters otherwise than by mutations of unknown cause.

A second speculation is that when one considers the difficulty of distinguishing the zygotes having various formulae even when dominance is comparatively perfect, he might expect a population of F_2 individuals with almost continuous quantitative variation if dominance is imperfect or absent. This gives a clue to a Mendelian interpretation of the inheritance hitherto known as blended.

The simplest case of this kind yet explained is the inheritance of a peculiar physical condition of the starch in maize (East and Hayes 1911). The varieties of maize known as flinty have the endosperm starch in a hard translucent or corneous condition. Those varieties known as dent have that portion of the starch immediately surrounding the embryo and that at the cap of the seed in a soft condition so that its great shrinkage while drying gives the kernel a dented appearance.

An eight-rowed yellow flint was crossed with a white dent and gave in F_1 an intermediate condition as regards the physical appearance of the starch. The selfed seeds of this generation gave ears in F_2 that ran the whole gamut from flint to dent. A few were like pure flint ears and a few were like pure dent ears, but the great majority were variously intermediate. When followed to the F_3 generation, however, one ear out of sixteen of the F_2 ears bred true to the dented condition and one out of sixteen bred true to the flinty condition. One cannot describe any particular character factors here, or say such and such a factor was contained by either variety. There is no doubt, however, but that the presence (or the absence) of two factors of some kind or other in the pure condition caused the one dent ear out of sixteen to breed true, and that the absence (or the presence) of these two factors in the pure condition caused the one flint ear out of sixteen to breed true. Furthermore, there is good evidence that factorial difference (without dominance) of *more than two* allelomorphic pairs causes the difference in physical appearance of the starch in other maize varieties.

From these facts, it is clear that one may give a valid Mendelian description to the behavior of those quantitative characters that give a blend in the F_1 generation. Two adequately supported assumptions must be made; first, that dominance is absent and that two doses (*i. e.*, the homozygous condition) of a factor have twice the effect of one dose; second, that independent factors cumulative in their operation are paired with their absence in the hybrid.

Let us assume a case of the so-called "blended" inheritance where all fluctuations due to environment are eliminated. A plant 12 inches tall is supposed to be crossed with a plant 28 inches tall. The difference between them is 16 inches. If this difference is due to one allelomorphic pair in which dominance is absent, the F_1 generation is all intermediate—about 20 inches—and the F_2 generation falls into three classes in which two represent the grandparental forms and one represents the F_1 form. Twenty-five per cent are 12 inches tall, fifty per cent are 20 inches tall, and twenty-five per cent are 28 inches tall.

Again, let us suppose this 16-inch difference between the parents to be represented by two allelomorphic pairs instead of one. The F_1 generation is again 20 inches tall, but instead of there being three classes in F_2, there are five classes, viz., 12, 16, 20, 24, and 28 inches, and they appear in the ratio 1:4:6:4:1. The grandparental types each appear once out of sixteen times.

The way this ratio is obtained is by simple recombination, but as dominance is absent, each time a *single* "presence" factor is added, the height is increased four inches.

$$
\begin{aligned}
9&\begin{cases} 1\ AABB = 28 \text{ inches.}\\ 2\ AaBB = 24 \text{ inches.}\\ 2\ AABb = 24 \text{ inches.}\\ 4\ AaBb = 20 \text{ inches.}\end{cases}\\
3&\begin{cases} 1\ AAbb = 20 \text{ inches.}\\ 2\ Aabb = 16 \text{ inches.}\end{cases}\\
3&\begin{cases} 1\ aaBB = 20 \text{ inches.}\\ 2\ aaBb = 16 \text{ inches.}\end{cases}\\
1&\{\ 1\ aabb = 12 \text{ inches.}
\end{aligned}
$$

If three independent size factors instead of two were involved in this cross, the F_1 individuals would fall in the same class as before, but the F_2 classes would be seven in number and the grandparental sizes would each be recovered only once out of sixty-four times. For four factors there would be nine classes of F_2 individuals, and the grandparental types would each occur only once out of 256 times; while with only eight factors, the forms of the grandparents would each appear only once out of 65,536 times, and it would be quite remarkable if they were ever recovered from an ordinary cross.

The entire scheme of this type of inheritance can be expressed in mathematical form just like ordinary Mendelian inheritance with full dominance. Let us recall that the F_2 Mendelian expression for n allelomorphic pairs when dominance is complete is the expanded binomial.

$(3 + 1)^n$ or $(\frac{3}{4} + \frac{1}{4})^n$
$n = 1 \ (3 + 1)^1 = 3 + 1$
$n = 2 \ (3 + 1)^2 = 3^2 + 3 + 3 + 1 = 9 + 3 + 3 + 1$
$n = 3 \ (3 + 1)^3 = 3^3 + 3(3)^2 + 3(3) + 1 =$
$27 + 9 + 9 + 9 + 3 + 3 + 3 + 1$

Likewise the expanded binomial $(\frac{1}{2} + \frac{1}{2})^{2n}$ or $(1 + 1)^{2n}$ gives the numerical relationships when dominance is absent and n represents the number of allelomorphic pairs. The expression $(\frac{1}{2} + \frac{1}{2})^{2n}$ instead of $(\frac{1}{2} + \frac{1}{2})^n$ is used because it is supposed that the presence of any allelomorphic pair in the heterozygous condition produces one-half the visible effect on the character that is produced when the genes are present in the homozygous condition. When n is very large the frequencies with which the different classes occur form a regular curve called the normal curve of error. This is the curve that is produced when the errors in any physical measurement are similarly plotted using as classes any constant deviation from the average, as a, 2a, 3a, etc. This same curve is also produced when one plots the fluctuations of any organic character produced by the infinite complexity of external conditions.

If no non-heritable fluctuations intervened to obscure the class to which any particular zygote belongs, therefore, one should expect the following classes in F_2 when parents of different sizes differing in n allelomorphic pairs are crossed. The extremes represent the grandparental types in each case, and the intermediate classes theoretically divide the difference between the parents into aliquot parts. It should be noted, however, that this is theory only; in reality the influence of one factor might be somewhat different from that of another factor.

$n=1$ 1 2 1............ = 4
$n=2$ 1 4 6 4 1........ = 16
$n=3$ 1 6 15 20 15 6 1..... = 64
$n=4$ 1 8 28 56 70 56 28 8 1.. = 256
$n=5$ 1 10 45 120 210 252 210 120 45 10 1 = 1024

Let us now note a few of the practical difficulties in interpreting breeding results that may follow this method of inheritance. In the theoretical example that we have used for the sake of clearness, it was assumed that there were no non-heritable fluctuations due to environment. Unfortunately this is not the case in nature. Fluctuations are everywhere present. They would obscure the classes to which individuals belong even if these class differences were very large. And since they are usually small, the change of individual form due to environmental causes makes it impossible to separate an F_2 population into the true classes to which each belongs theoretically. Nor is this the whole trouble. If the table showing the expected results with two pairs of size characters is examined, it is found that not all the individuals that belong to a particular size class have the same zygotic formula. For this reason one cannot pick out zygotes of a certain size and expect them to breed the same. Their potentialities are likely to be different. Furthermore, practical breeding results are undoubtedly complicated by cases of correlation. This correlation need not be gametic, tho such cases in all likelihood do occur; they may be merely physiological. For example, a maize plant might have the gametic possibilities of small plant size and large ear size, but it would be foolish to expect that a plant capable of only a limited amount of development could bear as large an ear as if it were, as a whole, capable of greater size development. Thus it must not be expected that theoretical possibilities are always expressed perfectly in nature, any more than it should be expected that theoretical physical calculations concerning known laws should agree perfectly with experimental data. The reproductive cells of plants and animals may indeed be described as mosaics of independently transmissible factors, but a plant or animal certainly can not be considered a mosaic of independent unit characters. These factors that appear to be independent in heredity act and react upon one another in complex ways during their development.

There is a means, however, by which it can be determined whether segregation does or does not occur in cases of seemingly blended inheritance. This is by comparing the variability* of the

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* In order to understand the data from these experiments it is necessary to be familiar with the meaning of several mathematical terms used

F_1, the F_2, and the F_3 generations. The fact that a blend occurs in F_1 does not mean that blended inheritance obtains. If it did, the F_2 and future generations should breed true to the type obtained in F_1. If, however, the variability of the F_2 generation is much greater than that of the F_1 generation, segregation and

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in the treatment of statistics. Should any reader be unfamiliar with their use, it is hoped that the following short explanation will make them clear:

When variations which are continuous in character are investigated, it is necessary to treat them arbitrarily as discontinuous variations. For example, in one of our studies of heights of maize plants we have put them into three-inch classes. The names of the classes are called the *class centers.* This means that the class whose center is 58 inches includes all the individuals from 57 inches to 59 inches inclusive. Any series of things thus measured and thrown into classes is known as a *frequency distribution*, the number in each class being the frequency with which the class occurs. Then if each class value is multiplied by the frequency with which it occurs, and the sum of these products divided by the total number, the average or *Mean* is obtained. Expressed mathematically,

$$A = \frac{\text{value} \times \text{frequency}}{\text{number}}.$$

With these data we are then able to compute a single number that expresses the variability of the frequency distribution from this mean. This number is called the *Standard Deviation* and is always denoted by the Greek letter Sigma (σ). It is found by getting the deviation of each class from the mean,—all values to the left of the mean being negative and all to the right positive,—squaring them, multiplying the squared deviations by their frequency, dividing the sum of these products by the total number of individuals, and extracting the square root of the quotient. The formula is $\sigma = \sqrt{\frac{\Sigma D^2 \times f}{n}}$, where Σ is the sign of summation. The value thus obtained is in terms of the unit values used. For example, in the distribution of plant heights in the table just mentioned, the standard deviation is in inches. To reduce this concrete value to an abstract one so that inches may be compared with pounds, centimeters, and so on, one has only to divide the Standard Deviation by the mean and multiply by 100. This gives us a measure of variability expressed in per cent known as the *Coefficient of Variability.* It is the best method we have of expressing variability as a single arithmetical term.

When terms like the Mean and the Standard Deviation are used, it is also convenient for us to know how much confidence to place in them. If we have 100 plants in one frequency distribution and 500 plants in another, common sense tells us to rely more upon the second distribution than upon the first. But to say just how much confidence to place in any calculated value, we determine what is known as the *Probable Error.* This value is preceded by the plus-or-minus sign ±. It means that there is an even chance that the true value is found within the limiting values made by adding to or subtracting from the calculated value the Probable Error. For instance, we say that a certain coefficient of variability is $6.49 \pm .32$. This means that the chances are even that the true coefficient of variability is within or without the values $6.49 + .32 = 6.81$ and $6.49 - .32 = 6.17$.

The class of greatest frequency is termed the *Mode.* When the frequency distribution is not symmetrical with respect to the mode it is said to be *skewed.*

TABLE 1.- *F_2 heights, frequencies, and formulae, and F_3 ranges, where parents differ in four factors*

Classes in inches	10	12	14	16	18	20	22	24	26	F_3 Nos.	F_3 Range	F_3 Groups
F_2 Frequencies	1	8	28	56	70	56	28	8	1	256	16 inches	
Zygotic Formulae and Frequencies in F_2 and Range of Variation in F_3, the latter in parentheses	I 1 *aabbccdd* — 1 **(Breeds true)**	VI 2 *Aabbccdd* 2 *aaBbccdd* 2 *aabbCcdd* 2 *aabbccDd* — 8 **(10-14 inches)**	II 1 *AAbbccdd* 1 *aaBBccdd* 1 *aabbCCdd* 1 *aabbccDD* — 4 **(Breed true)** X 4 *aaBbCcdd* 4 *aaBbccDd* 4 *aabbCcDd* 4 *AaBbccdd* 4 *AabbCcdd* 4 *AabbccDd* — 24 **(10-18 inches)**	VII 2 *AABbccdd* 2 *AAbbCcdd* 2 *AAbbccDd* 2 *AaBBccdd* 2 *aaBBCcdd* 2 *aaBBccDd* 2 *AabbCCdd* 2 *aaBbCCdd* 2 *aabbCCDd* 2 *AabbccDD* 2 *aaBbccDD* 2 *aabbCcDD* — 24 **(14-18 inches)** XIII 8 *aaBbCcDd* 8 *AabbCcDd* 8 *AaBbccDd* 8 *AaBbCcdd* — 32 **(10-22 inches)**	III 1 *AABBccdd* 1 *AAbbCCdd* 1 *AAbbccDD* 1 *aaBBCCdd* 1 *aaBBccDD* 1 *aabbCCDD* — 6 **(Breed true)** XI 4 *AAbbCcDd* 4 *AABbccDd* 4 *AABbCcdd* 4 *aaBBCcDd* 4 *AaBBccDd* 4 *AaBBCcdd* 4 *aaBbCCDd* 4 *AabbCCDd* 4 *AaBbCCdd* 4 *aaBbCcDD* 4 *AabbCcDD* 4 *AaBbccDD* — 48 **(14-22 inches)** XV 16 *AaBbCcDd* 16 **(10-26 inches)**	VIII 2 *aaBbCCDD* 2 *aaBBCcDD* 2 *aaBBCCDd* 2 *AabbCCDD* 2 *AAbbCcDD* 2 *AAbbCCDd* 2 *AaBBccDD* 2 *AABbccDD* 2 *AABBccDd* 2 *AaBBCCdd* 2 *AABbCCdd* 2 *AABBCcdd* — 24 **(18-22 inches)** XIV 8 *AABbCcDd* 8 *AaBBCcDd* 8 *AaBbCCDd* 8 *AaBbCcDD* — 32 **(14-26 inches)**	IV 1 *aaBBCCDD* 1 *AAbbCCDD* 1 *AABBccDD* 1 *AABBCCdd* 4 **(Breed true)** XII 4 *AABbCcDD* 4 *AABbCCDd* 4 *AABBCcDd* 4 *AaBbCCDD* 4 *AaBBCcDD* 4 *AaBBCCDd* — 24 **(18-26 inches)**	IX 2 *AaBBCCDD* 2 *AABbCCDD* 2 *AABBCcDD* 2 *AABBCCDd* — 8 **(22-26 inches)**	V 1 *AABBCCDD* 1 **(Breeds true)**	16 64 96 64 16	Breed true 4 inches 8 inches 12 inches 16 inches	I-V VI-IX X-XII XIII, XIV XV

recombination of gametic factors of some kind must have taken place, for in no other way could this greater variability be explained. Contributions toward such proof have been given by the essential agreement of the investigations reported by at least eight investigators.

Perhaps before giving a brief résumé of the results of these investigations, however, it may be well to illustrate by concrete hypothetical examples just what sort of complexities the data from actual crosses are likely to show if the theory of multiple factors is correct. The practical difficulties of proving this theory have been mentioned in general terms; let us see in what form these difficulties are likely to present themselves to us in our actual experiments.

Returning to a simple case like that used before, in which the difference in height between a 10-inch plant and a 26-inch plant is supposed to be due to four independent, interchangeable, allelomorphic pairs, let us examine the results that are to be expected in the F_1, F_2, and F_3 generations and in back crosses between an F_1 individual and either parent. In this example the presence of any *single* factor is supposed to add 2 inches to the height of a zygote and all effects of environment on development are assumed to be absent.

Plant A, 10 inches high, has the zygotic formula $(x = 10 \text{ in.}) + aabbccdd = 10$ inches, the plant B has the zygotic formula $(x = 10 \text{ in.}) + AABBCCDD = 26$ inches. Since all F_1 plants have the zygotic formula $(x = 10 \text{ in.}) + AaBbCcDd$, they are all 16 inches high. If we apply the formula $(\frac{1}{2} + \frac{1}{2})^8$ for determining the frequency distribution of the F_2 generation, the following result is obtained:

Classes in inches.	10	12	14	16	18	20	22	24	26
No. of individuals.	1	8	28	56	70	56	28	8	1

Thus, while the plants of the F_1 generation are alike, the F_2 generation is variable. The class of greatest frequency is the same as that of the F_1 generation, but it is really made up of individuals unlike in zygotic constitution and which therefore breed very differently in F_3 as is shown in Table 1.

One can see clearly what different progenies these various zygotes will produce. Zygotes selected at random from the extremes will be more likely to breed comparatively true to their type than will those near the class of greatest frequency. Thus of the 74 zygotes 10 to 14 and 22 to 26 inches high, 10, or 13.5 per cent, will breed true; 16, or 21.6 per cent, will produce progenies with ranges of variation of only four inches; and 48, or 64.9 per cent, will produce progenies with ranges of eight inches. Of the 182 zygotes 16 to 20 inches high, only 6, or 3.3 per cent, will breed true; 48, or 26.4 per cent, give progenies with four-inch ranges; 48, or 26.4 per cent, give progenies with eight inch ranges; 64, or 35.2 per cent, give progenies with twelve-inch ranges; and 16, or 8.7 per cent, give progenies with sixteen-inch ranges. The old biometrical idea that the class of greatest frequency is the *type* of the population toward which all selected individuals tend to revert is therefore erroneous. It is true, however, that if a large number of size factors were heterozygous in the F_1 generation, the grandparental types would be recovered so infrequently that practically there would be a sort of blended inheritance. One could obtain races that bred comparatively true for all of the grades intermediate between the parents, but the nearer he was working for an absolute blend the easier would be his work when he was able to raise only a few individuals in each generation. He could, nevertheless, cross extreme sizes and expect to recover either grandparental size combined with any other good quality possessed by the other grandparent if he could deal with sufficiently large numbers.

Passing now to the question of back crosses, the interesting problem arises as to whether the F_1 crossed with either parent gives data which are easier to analyze than are those obtained from breeding the F_1's *inter se.* When parents representing a single allelomorphic difference in a qualitative character are crossed, the "F_1 × the recessive parent" gives heterozygous dominants and homozygous recessives in equal numbers. It is easier to determine a 1:1 ratio than a 3:1 ratio; therefore backcrossing is a popular method in genetics. But in the cases we are discussing, no aid to factoral analysis is obtained from backcrossing. Backcrossing F_1 with either parent gives a frequency curve exactly like that obtained from breeding the F_1 individuals *inter se.* When crossed with the small parent, the distribution of the progeny is from the size of the small parent on the one hand to the size of the F_1 on the other; when crossed with the large parent, the distribution is from the size of the F_1 on the one hand to the size of the large parent on the other. The frequencies of the classes between these extremes is found by expanding the binomial $(\frac{1}{2}+\frac{1}{2})^n$ instead of $(\frac{1}{2}+\frac{1}{2})^{2n}$ as is done in the case of interbreeding the F_1 individuals.

Unfortunately one can never meet in practice a case as simple as our hypothetical one. The first perplexing factor is environmental influence. External conditions influence the whole development of both plants and animals, but nowhere is their effect so great as on size characters. In studying the heredity of size characters, therefore, one is not only confused by the fact that individuals of a certain theoretical size have different genetic possibilities, but is literally overwhelmed with difficulties by the knowledge that these theoretical sizes are *pushed upward and downward* by external causes. One does not know when he selects an individual of a certain size *whether it even belongs in the class in which it appears.* Besides this trouble, the stimulus to development due to heterozygosis also causes confusion. It is well known that hybrids often exceed their parents in size. This phenomenon is not one of heredity but one of conditions due to heredity. There is a greater stimulus to development when a character is in the heterozygous condition than when it is in the homozygous condition. Moreover this stimulus is in some degree cumulative. It increases roughly with the number of heterozygous factors. For this reason it is a force that aids environment in *pushing* individuals that theoretically should be in one size class into a different class.

But these are not the only troubles. One is not often—if ever—able to cross two plants in which any particular size difference can be represented by a notation like $(X = 10 \text{ inches}) + aabbcc$ and $(X = 10 \text{ inches}) + AABBCC$. A great majority of plants are frequently crossed thru insect or other agencies, while a comparatively large number have flower structures of such a character that they are always cross-fertilized. Heterozygosis is also favored by bisexuality wherever it occurs. Many plant varieties are therefore hybrid complexes from which types of different kinds can be isolated by inbreeding. Other plants which are especially adapted to self-fertilization may be homozygous in nearly all their gametic factors, for self-fertilization tends to eliminate heterozygosis. But such cases are not common. Ordinarily one may presume that the two individuals he wishes to cross are heterozygous for a considerable number of factors. This reduces the excess of variability which the F_2 generation might be expected to show over that shown by the F_1 generation. Furthermore, it gives an F_1 generation in which the zygotic constitution of each individual is not the same as would be the case were both parents completely homozygous. A series of F_2 generations raised from different F_1 individuals, for this reason, may be quite different in their variability.

On the other hand, it may sometimes happen that the variability of the F_2 generation exceeds that of the F_1 generation in a degree unsuspected by the difference in size of the parents. East (1910) predicted that if the theory of multiple interchangeable segregating factors gave a true interpretation of the behavior of quantitative characters in crosses, cases would be found when parents identical in size would show marked size recombinations in F_2. The reasons for such a phenomenon are these. Two plants are the same size. The size in plant No. 1 is due to the influence of factors "*AABBCC*," the size in plant No. 2 is due to the influence of factors "*DDEEFF*." Three interchangeable factors in the homozygous condition have produced the same size effect in each case. But no one of these factors in plant No. 1 is allelomorphic to a factor in plant No. 2. The F_1 generation is therefore theoretically about the same size as either parent, for there are six factors present in each case. The fact that in one case these six factors are made up of three homozygous allelomorphic pairs, and in the other case by six heterozygous allelomorphic pairs, makes no difference in the size produced (leaving out of consideration the stimulus due to heterozygosis). In F_2, on the other hand, recombination gives a frequency distribution far above and far below this typical size. It is the distribution obtained by expanding the binomial $(\frac{1}{2}+\frac{1}{2})^{12}$. In fact, it is exactly what would have occurred if a plant "*aabbccddeeff*" had been crossed with a plant "*AABBCCDDEEFF*."

Recently Hayes (1912) has reported a fulfillment of this prediction. He crossed two varieties of *Nicotiana tabacum* and studied the inheritance of number of leaves. In both varieties the mean number of leaves was about 20 (see Table 2), and the model class about 20. The variability of each variety was small: for the "Cuban" variety it was 7.53 ± .293 in the first year studied and 5.29 ± .227 in the second year studied, while for the "Havana" variety it was 6.98 ± .272 the first year and 8.87 ± .345 the second year. The mean, the mode, and the variability of the F_1 generation were about like those of the parents. The coefficient of variability was 6.10 ± .237. The F_2 generation, however, showed a range of variability so much greater than the F_1 generation that it can hardly be questioned that segregation and recombination of several "leaf-number" factors has occurred. The coefficient of variability was 15.84 ± .549.

Cases of the same kind are reported later in this paper. (See Table 33 and Table 38).

TABLE 2.—*Frequency distribution of number of leaves per plant of cross between two varieties of Nicotiana tabacum.*

Number	Year grown	Leaves of parent	Leaf classes																				Total	Mean	Stand. Dev.	Coef. Var.
			14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33				
405 Cuban	1910	....	......	......	1	7	16	37	36	35	12	4	1	1	......	......	......	......	......	......	......	......	150	19.9 ± .082	1.50 ± .059	7.53 ± .293
405-1	1911	21	......	......	......	......	3	16	34	46	20	5	......	......	......	......	......	......	......	......	......	......	124	20.6 ± .066	1.09 ± .047	5.29 ± .227
402, Havana	1910	....	......	......	......	3	22	44	42	22	10	6	1	......	......	......	......	......	......	......	......	......	150	19.8 ± .076	1.38 ± .054	6.98 ± .272
402-1	1911	20	......	......	1	10	11	23	34	31	16	12	3	2	......	......	......	......	......	......	......	......	143	20.3 ± .101	1.80 ± .072	8.87 ± .354
(402x405) F1	1910	....	......	1	1	3	8	39	60	30	7	......	......	1	......	......	......	......	......	......	......	......	150	19.8 ± .067	1.21 ± .047	6.10 ± .237
(402x405)-1 F2	1911	20	3	4	8	8	20	18	30	24	25	17	16	5	4	3	1	1	1	1	2	1	192	20.9 ± .161	3.31 ± .114	15.84 ± .549

Note. 405-1 is a frequency distribution of the progeny of a single self-fertilized plant of 405, and 402-1 is a frequency distribution of a single self-fertilized plant of 402.

Let us now consider the experimental evidence that is thought to show segregation and recombination of factors of the kind that have just been discussed.

Nilsson-Ehle in 1908 stated that he had found greater variability in F_2 than in F_1 in numerous crosses where the parents differed in quantitative characters. Data were presented, however, only on qualitative characters.

East (1910), in his independent proposal of this method of interpreting the inheritance of quantitative characters by a Mendelian notation, showed how certain data on the inheritance of different numbers of rows of seeds on the ear of maize could be thus analyzed. His observations were not sufficiently numerous, however, to be convincing.

A little later Emerson's (1910) paper on inheritance of quantitative characters appeared. Here segregation and recombination of size factors was clearly shown in three species; viz. *Cucurbita pepo*, *Phaseolus vulgaris*, and *Zea mays*.

Cucurbita pepo. A cross between a long, narrow Crookneck squash and a round flat Scallop squash gave an F_1 generation intermediate in all respects and an F_2 generation showing a complete series of sizes and shapes running from that of the Crookneck to that of the Scallop. The Means and Coefficients of variation were as shown below. The Probable Errors were not calculated but the number of individuals was large enough for one to have considerable confidence in the results.

Race or hybrid	Means		Coefficients of variation	
	Length	Diameter	Length	Diameter
	Cm.	*Cm.*	*Per cent*	*Per cent*
Crookneck	39.6	11.4	17.0	12.0
Scallop	7.4	17.8	15.8	12.6
F_1 hybrid	17.5	17.5	19.0	12.6
F_2 hybrid	19.6	13.2	42.7	58.8

A cross between a long narrow Spoon gourd and a shorter, much thicker Horned gourd gave a similar increase of variability in F_2 over that shown by F_1.

Race or hybrid	Means		Coefficients of variation	
	Length	Diameter	Length	Diameter
	Cm.	*Cm.*	*Per cent*	*Per cent*
Horned	10.3	9.0	9.4	9.9
Spoon	14.0	4.2	15.6	16.0
F_1 hybrid	12.9	5.6	15.8	15.7
F_2 hybrid	15.7	5.5	37.5	21.2

Phaseolus vulgaris. A large number of crosses between beans differing in length, breadth, weight, and thickness were made. These, one and all, showed segregation and recombination in F_2. A few cases recorded behaved as shown in the following table. It should be noted, however, that the F_2 generation was grown in the winter in a greenhouse, while the F_1 generation was grown in the open field. Any effect that this difference of environment would have on the variability would probably be towards a smaller variability for the greenhouse-grown plants.

Race or hybrid	Means				Coefficients of variation			
	Weight	Length	Breadth	Thickness	Weight	Length	Breadth	Thickness
	Cg.	*Mm.*	*Mm.*	*Mm.*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Fillbasket	32.2	13.8	7.6	4.4	7.93	3.22	2.20	3.78
Longfellow	28.3	12.9	5.6	4.6	6.09	3.27	3.57	4.54
F_1 hybrid	28.4	13.0	6.5	4.7	7.63	3.53	1.43	3.37
F_2 hybrid	36.8	14.1	7.0	5.0	17.43	8.83	10.33	9.45
Fillbasket	32.2	13.8	7.6	4.4	7.93	3.22	2.20	3.78
Snowflake	16.4	8.3	5.7	4.7	9.40	2.89	3.68	5.38
F_1 hybrid	25.4	11.4	6.4	4.5	9.90	3.47	2.70	3.83
F_2 hybrid	28.6	11.3	6.9	4.8	24.48	8.32	5.96	8.95

Emerson also reported segregation of size of seed and height of stalk in F_2 when maize varieties differing in those characters were crossed. These results will not be discussed for they are reported in full later in this paper. For the same reason, the papers of East (1911) and East and Hayes (1911) reporting segregation of number of rows, height of stalk, size of ear, and size of seed in maize will not be considered here.

Shull (1910) also reported observations on the number of rows on the maize ear, showing that while an F_1 population is no more variable than the pure strains from which it came, the F_2 population is much more variable.

In 1911 an excellent paper of Tammes (1911) appeared. Miss Tammes made many crosses between varieties and between species in the genus *Linum*, and studied the inheritance of such characters as length and breadth of seed and length and breadth of the petals. A cultivated flax known as Egyptian with seeds varying from 5.0 mm. to 6.9 mm. in length was crossed with *Linum angustifolium* whose seeds vary from 2.4 mm. to 2.6 mm. in length. The seeds of the F_1 generation were intermediate, varying from 3.6 mm. to 4.2 mm. The range of variability in the F_2 generation, on the other hand, was very large, ranging from 2.8 mm. minimum to 4.7 mm. maximum. A second cross between another cultivated flax with a minimum seed length of 3.5 mm. and a maximum seed length of 4.5 mm., with *Linum angustifolium* gave F_1 seeds varying in length from 3.0 mm. to 3.5 mm. and F_2 seeds varying in length from 2.3 mm. to 4.2 mm. In opposition to these species crosses giving a comparatively uniform F_1, a cross between the two varieties Common Flax and Egyptian flax and its reciprocal gave a variable progeny, tho here, too, an intermediate character was manifested. Further, the F_2 was but little more variable than the F_1. Altho this result might easily be explained by gametic impurity of the parents, it was so interesting that the progeny of extreme individuals was followed to the F_3 generation. There was no doubt, from the data obtained in this generation, that various F_2 plants did have different gametic formulae, for the progeny produced were different. A somewhat similar result was obtained when Egyptian flax was crossed with *Linum crepitans*.

Length and breadth of petals was studied in a cross between Egyptian flax and *Linum angustifolium* and its reciprocal. In both cases the variability of F_2 was greater than that of F_1.

In Nilsson-Ehle's extended monograph of 1909, it was stated that crosses of wheats and of oats were in progress in which such characters as number of seeds per head, hairiness, height, length of glume, length of spike, size of seed, hardiness, and resistance to rust were being studied. In 1911 that portion of his results relating to the internodal length of wheat spikes and resistance to rust was reported. Some of the various crosses had been followed to the F_3 generation. The data show clearly that varietal differences in these characters depend on several independent gametic factors, altho their exact behavior is not known. Possibly complete analysis of such a thing as resistance to a fungal parasite cannot be cleared up by field work, as Nilsson-Ehle believes, for there is evidence that genotypic differences in the parasites exist which complicate matters.

Hayes' (1912) paper on tobacco has already been mentioned in another connection. He presented data upon number of leaves per plant, height of plant, and size of leaf. In each case there was a greater variability in F_2 than in F_1, and this difference he shows clearly can be most logically described by assuming segregation and recombination of "size" factors.

Von Tschermak (1902) some years ago found that an early blossoming pea crossed with a late blossoming variety gave an intermediate F_1 and a variable F_2. Afterwards he found (1904) that only a portion of the "early" and "late" segregates bred true, and that this behavior could not be expressed by a simple Mendelian formula. In a recent paper (1912) he gives a full analysis of his later results on this character complex, and expresses them with the Mendelian notation by assuming multiple factors.

Belling (1912) has reported a study of a cross between two bean varieties that differed in many characters. In such quantitative characters as time of flowering, size of pod, and size of seed, there seems to be no question but that factors have segregated and recombined. In the F_2 generation there was invariably great variability, and in several cases extremes appeared that were beyond the grandparental types. The author does not commit himself further than to say that segregation has occurred, but the data that he presents are exactly what should be expected on the multiple factor interpretation.

Phillips (1912) has studied the inheritance of body weight in a cross between the large French Rouen duck and the small domestic mallard. The first named variety is more than double the weight of the latter. He concludes that: "The amplitude of variation of the F_2 animals is greater than that of the F_1 animals, but does not extend beyond the nearer limit of the respective grandparental races." As a matter of fact, with an F_2 population of only 33 individuals it is remarkable that the variability was so great.

In addition to these papers giving the results of actual investigations, Lang (1911) has published a long article showing how the results of Castle (1909) on ear length of rabbits might have a Mendelian interpretation by using Nilsson-Ehle's scheme. As Lang might have suspected, Castle had already acknowledged (in public lectures) the possibility of such an interpretation, an acknowledgment that was afterwards published (Castle 1911).

METHODS AND MATERIALS USED.

The methods employed in making these studies, including the growing of the plants, guarding the pollination, recording the data, etc., have been given in detail in previous papers (East and Hayes 1911 and Emerson 1911). A brief statement here will therefore suffice. In so far as possible the different generations of the various crosses and representatives of the parent varieties have been grown together in the same season. Where comparisons are made between lots grown in different years the fact is indicated in the tables or accompanying text. The various lots to be compared have always been grown on the most nearly uniform soil available. In most cases certain plantings have been duplicated in different parts of the field, but it has not been possible to carry out this plan as fully as might be desired. Careful planting of seed, placing label-stakes in the field, and recording the position of the different lots on planting plans have practically removed the possibility of mistakes in identification.

In the production of hand-pollinated seed, both staminate and pistillate inflorescences have been protected with heavy manilla bags. In the transfer of pollen from the tassel-bags to the silks great care has been exercised to prevent the entrance of undesired pollen. After pollination each ear has been rebagged and a label tag attached to it. The experimental error in regard to pollination is believed to be not greater on the average than about one seed per ear. (See East and Hayes 1911.)

The measurements of height of plant were made in the field. The main stalk of each plant was chosen for measurement and the distance from the surface of the ground to the top of the tassel determined. The number of nodes was determined by counting the leaves, except near the base of the stalk, where it was necessary to make a more careful examination. It is probable that not all the basal nodes were noted, but any slight error of that sort is not serious, for, since all counts for the several families of any one series were made by one person, the same error would likely be made in case of each lot. The ears were measured after having been harvested and allowed to dry. Time of flowering was noted at approximately the same time each day. At each examination any plant whose staminate flowers had begun to open was tagged with a label bearing the date and the individual number of the plant.

The frequency distributions and the computations of statistical constants have all been checked over once, and, where practicable, this has been done by a second person.

It is not claimed that no errors have been made in connection with the studies, but great care has been taken to avoid them and it is our belief that the data presented are essentially accurate.

The plants of California pop and of Tom Thumb pop used in making crosses with Missouri dent and also the plants from which the later representatives of these varieties were grown were from seed obtained from seed dealers. The Missouri dent plants used in crossing and those from which all later lots of this variety came were from a single open-fertilized ear obtained from an exhibitor at the National Corn Exposition held at Omaha. Neither of these varieties, therefore, had been self-pollinated before the experiments were begun. The other varieties used in these experiments were in most cases selfed for at least two generations before being crossed, but in some cases there were used parent ears obtained from commercial growers who made a specialty of the types furnished. In general, the descriptive notes below include only such characters of the several varieties as were made use of in the experiments reported in this paper.

The strain of Tom Thumb used in the cross with Missouri dent is a very dwarf and very early pop corn. The plants tiller considerably and have short stalks with few nodes. The tillers are mostly shorter than the main stalk and frequently end in an ear instead of in a tassel. The silks protrude from the leaf sheaths in advance of the ear-shoots and some days before the pollen is shed. The ears are very short and usually have about twelve rows of small, smooth, flinty grains.

California pop is also a dwarf corn, but the stalks are considerably taller than those of Tom Thumb and have nearly twice as many nodes. The tillers are more numerous than in Tom Thumb, are mostly of about the same height as the main stalk, and like it have one or more ears and end in a tassel. The ears are even smaller than those of Tom Thumb and contain numerous, irregularly arranged grains. The latter are sharply rice-pointed and considerably smaller than the grains of Tom Thumb. Unlike Tom Thumb this variety is very late in flowering and in ripening.

Missouri dent is a large late corn. It blossoms at about the same time as California pop, but matures somewhat later. The stalks are tall and stout and have few tillers. The latter are often short and without tassels or ears and, when tall, almost always end in a tassel, but frequently lack ears. The ears are rather short for dent corn, but are large in diameter and contain numerous rows of kernels—most commonly sixteen to twenty. The grains are of a fairly smooth dent type and medium broad for corn of that type. They are, of course, very much larger than the grains of either one of the two pop corn varieties.

The strain of Tom Thumb (No. 60) used in crosses with Black Mexican was similar to the strain described above in height of stalks, number of tillers, earliness, etc., but had slightly smaller ears and seeds.

Black Mexican sweet (No. 54) has medium tall stalks and fairly numerous tillers. Its ears are long and almost always have eight rows of rather broad, wrinkled grains.

Watson flint (No. 5) has medium short stalks and very long ears with eight rows of grains as the prevailing type.

Leaming dent (No. 6) has very tall stalks and long ears with from 12 to 20 rows, 16 rows being the modal condition.

Of the varieties used in the other crosses, only one character—number of rows—is of direct concern to us here. Illinois low protein (No. 2) is a dent corn with 12 to 20 rows and a mode of 16 rows. Illinois high protein (No. 8) is a 12-rowed dent with a range from 10 to 18 rows. Early Crosby (No. 18) is a 12-rowed sweet corn ranging from 8 to 14 rows. Sturges' flint (No. 11) is strongly 12-rowed in type, only a few ears having other row numbers ranging from 8 to 16. Longfellow flint (No. 15) is an 8-rowed type, rarely ever having ears with any other number of rows.

INHERITANCE OF NUMBER OF ROWS PER EAR.

The maize ear may be regarded either as a fusion of four or more spikes, each joint of the rachis bearing two spikelets, or as meristic variations or repetitions of a rachis bearing two spikelets. The rows are paired, and no case is known where a member of a pair has been aborted. De Vries has regarded the number of rows on the maize ear as continuous variations which are inherited in a somewhat temporary manner. He came to this conclusion from a selection experiment in which he was able to increase the number of rows in the variety with which he was working, from an average of about 13 rows per ear to an average of about 20 rows per ear in seven years, only to find that the selected variety gradually reverted to the type of the original variety when selections ceased. We do not question these facts but the interpretation that de Vries gave to them. The work of East, Emerson, Hayes, and Shull has shown conclusively that the reversion in de Vries' selected strains came about simply thru the intercrossing of the progeny of plants that were somatically alike but genotypically different. The evidence presented here shows that the character complex of number of rows per ear is made up of a series of cumulative unit factors independent in their inheritance.

Altho there seems to be no good reason why this character complex should not be considered to be of the same nature as that of other size characters in which variation appears to be continuous, it possesses the advantage of being divisible into a discontinuous series of numbers. From such a numerical series one can obtain some idea of the prevalence and magnitude of non-inherited fluctuations. A large number of counts of the number of rows of both ears on stalks that bore two ears has shown a variation which is usually ±2 rows, altho it may be as high as ±4 rows. An ear which appears to belong to any particular class, therefore, may be pushed by external conditions into the wrong class, but the proper class will be one of five in which the apparent class is the central one. All ears, however, do not have the same ability to respond to external stimuli. The 8-rowed condition, which is the last subtraction form in which maize appears, may be selected until the strain breeds very true. In a count of the population of an isolated maize field where Longfellow, an 8-rowed flint, had been grown for many years, 4 four-rowed, 993 eight-rowed, 2 ten-rowed, and 1 twelve-rowed ears were found. On the other hand, a Leaming dent, selected for many years and inbred by hand for six generations, still gave a range of variation from 12 to 20 rows. Part of this difference in behavior shown by races with a low number of rows and races with a high number of rows is undoubtedly due to correlation with other characters—both physiological and gametic—but at the same time it is more reasonable to suppose that an ear which can vary in any one of eight spikes will show a greater degree of fluctuation than one which can vary only in any one of four spikes. For this reason it is likely that strains with a high number of rows will never show the low variability seen in strains with a low number of rows.

Taking into consideration the probable amount of fluctuating variation, several interesting points are presented in the tables showing the frequency distributions of the number of rows per ear in the various crosses.

Tables 3, 4, and 5 show the results from three different crosses in which No. 5,* an 8-rowed white flint, was crossed with other varieties. In Table 3 the male parent was No. 6, the well known Leaming dent. In the particular strain from which this male parent was taken, the modal condition (that is, the class of greatest frequency) was sixteen. Four F_2 families were grown, of which only one was markedly more variable than the F_1 generation. The modal condition of F_1(12) was intermediate between the two parents. In three of the F_2 families, the modal condition was ten; in the remaining family it was twelve. In Table 4, the male parent, a white dent, was also typically twelve rowed. The F_1 and F_2 generations were comparable to those in Table 3. While the F_2 generation was much more variable than the F_1 generation, no great confidence can be placed in the results, owing to the meager numbers of the F_1 generation. Table 5 shows a peculiar result. Here No. 5 was the male parent, while the female parent was a 12-rowed flint which is very low in variability. Both the F_1 and F_2 generations were typically twelve rowed.

These data form the basis for several speculations. In two crosses the typical condition of the hybrid was intermediate. In this last cross the 12-rowed condition appears to be dominant. Is this due to the fact that the 12-rowed parent was the mother? Is it due to the fact that the maternal individual was gametically 16 rowed? Is it due to there being few differences between the parents by which complications thru correlation might arise, for both are flints? It seems probable that the last two suggestions are likely to be at the basis of the phenomenon, but there is no way of deciding from the evidence at hand.

Table 6 merely shows that this same 12-rowed variety when crossed with another variety which is typically twelve rowed shows no greater variability than one of the parents.

Table 7 gives the data from a cross between an 8-rowed flint and a very variable 12-rowed dent. The description of the F_1 generation was not taken at the time, as the cross was made primarily to study another question. The omission is partially covered by the data from nine ears that were selfed artificially. The interesting part of the record is decidedly the F_3 families, for they arose from three ears, each having a different number of rows. The 8-rowed mother gave progeny with a few more 10-rowed ears than 8-rowed ears, but one can see what a tendency there is toward the 8-rowed condition. It would probably be very easy to recover a typical 8-rowed race in the next generation. On the other hand, the progeny of the 14-rowed mother is a variable family with the modal condition at 14 rows. The number of ears exceeding this condition is sufficient to lead one to believe that a race like the No. 8 parent would be as easy to obtain as the one like the No. 15 parent. But this could not be done, we believe, by selecting ears having the flint condition. There is certainly some sort of a correlation between the dent condition and a high number of rows, for all of the ears with a high number of rows are dent in character.

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* For description of these varieties see page 29.

This dent, No. 8, was also crossed (Table 8) with an 8-rowed sweet, No. 54 (Black Mexican). *Nine F_3 families were grown in this cross, and strains exactly like each parental condition were recovered.* The progeny of (8x54)1-13 are as typically 8-rowed as the Black Mexican variety, while the progeny of No. (8x54)1-5 and No. (8x54)1-6 are practically like No. 8, in number of rows, tho they both differ in other characters.

Tables 9, 10, and 11 are similar to Table 8. Different individuals belonging to the commercial varieties known as Tom Thumb and Black Mexican were crossed. This gives one some idea of the various gametic possibilities within what might be considered single races. No. 54 is a comparatively pure 8-rowed race, but No. 60, since it produces individuals having from 8 to 16 rows, may be expected to have various potentialities.

Table 9 lists the data from the cross known as 60-3x54. The F_1 generation is very variable, if confidence can be placed in a population of only 33 ears. Three F_2 families were grown. Family (60-3x54)-1 grew from a 16-rowed ear, and shows clearly that it had within it possibilities different from those of ears (60-3x54)-5 and (60-3x54)-6, the other two ears that produced F_2 families. In fact, tho ear (60-3x54)-1 produced no daughter ears with *less* than 12 rows, ear (60-3x54)-6 produced no daughter ears with *more* than 12 rows. No further proof is necessary to show that one of the parental plants was heterozygous for certain of the factors necessary for the production of rows greater than eight in number. The F_1 individuals, in other words, were different in gametic constitution.

Even the family (60-3x54)-1 contained individuals heterozygous for several factors, moreover, tho apparently it was somewhat low in variability. This is shown by the varied appearance of the progeny of the four ears from it that were followed into the F_3 generation. The progeny of ear (60-3x54)1-1EO, a 16-rowed ear, showed a modal condition of 16 rows, with ears having both 18 and 20 rows. None had less than 12 rows, but this undoubtedly was an accidental circumstance because the 12-rowed class occurred 15 times. In a perfect sample of the population, therefore, one would expect to find individuals with both 10 and 8 rows. At the same time the modal condition of this family was unquestionably sixteen rows, while that of the other three families was twelve, fourteen, and twelve. This result is very striking when compared with the F_3 families (60-3x54)-5-3 and (60-3x54)6-5, where the modal conditions are 10 and 8, respectively.

Five F_2 families of the cross 60-5x54 (Table 10) were grown. These were again different in character. Family (60-5x54)-6 was characteristically twelve rowed, while family (60-5x54)-11 was characteristically 8 and 10 rowed. Unfortunately only a single 8-rowed ear from family (60-5x54)2 was carried to the F_3 generation and its progeny tended to form an 8-rowed type. Most remarkable for its tendency to form a non-variable family, however, was family (60-5x54)-11. Five ears were grown and in each there was a notable tendency toward an 8-rowed strain. It may be doubted very seriously whether selection toward a 16-rowed type in all of these families would be successful. Success might come in one or two instances,—for gametic possibilities of a 16-rowed race may still exist in some of the families,—but it would not be likely in every family. On the other hand, the two fraternities raised from ears (60-5x54)12-1ES and (60-5x54)-12-2ES are very high in variability and show that they contain potentialities of yielding races averaging from 16 to 20 rows.

In cross 60-8x54, Table 11, a race characteristically 8 rowed and a race characteristically 12 rowed were obtained in the F_3 generation.

In Table 12 are presented data derived from a cross of Tom Thumb pop and Missouri dent. Few records are available except those of F_2 and F_3 families grown in 1911. No F_1 generation was grown in 1911 and the records of F_1 ears produced in 1910 were accidently destroyed. There are entered in the table, however, under the designation of F_1 generation, such records as were obtainable from the ears kept as samples. Tho both parent varieties were grown in 1911, no record was obtained of the ears of Missouri dent since this variety failed to mature in Massachusetts. Owing to poor germination only a few plants of Tom Thumb pop were grown in 1911 and these, because of the unfavorable weather in early summer, while they were developing, and perhaps also because of previous selfing, produced few ears. The entries in the table under the designation of Tom Thumb pop and of Missouri dent, like those of the F_1 generation, were obtained from such ears of these varieties as had been preserved as samples.

Such data as are available indicate a 12-rowed type for Tom Thumb pop. The range of variation indicated for Missouri dent suggests that the stock of that variety used may have been heterozygous for several factors for number of rows, with a tendency to produce 16 to 20 rows per ear. The three F_2 families, 510 grown in Nebraska in 1910 and 1127 and 1128 grown in Massachusetts in 1911, were somewhat different in the mean number of their rows and in their ranges of variation. Such behavior as this was to have been expected if either or both of the parents were heterozygous for any of the factors concerned in determining number of rows per ear. The range of variation in the F_2 fraternities extended somewhat beyond the extreme ranges of the parent varieties—if indeed the records available can be said to show the ranges of the parents.

The best evidence of real segregation in F_2 of the factors for number of rows is furnished by the F_3 families. As pointed out more fully later, in the discussion of inheritance of height of stalk, the differences between the several F_3 lots under consideration here cannot be ascribed to the possible heterozygous condition of the parent plants used in this cross, because all the F_3 families are descendants of one F_2 fraternity, No. 510, which in turn, of course, was the progeny of a single F_1 plant. What other F_2 progenies or other F_1 plants may have been like or even what other sorts of gametes the parent plants may have produced, in addition to the two gametes whose union resulted finally in these F_3 families, is absolutely immaterial. Since all these F_3 families were related in this way, their differences are ascribable only to segregation of size factors in F_2. Among the F_3 lots, there were included at least one 12-rowed type, 1142, like Tom Thumb pop, several lots of a 16-rowed type, and two or three of a 20-rowed type, particularly 1140 and 1141, with perhaps also 14-rowed and 18-rowed types, 1144, 1134, 1135, etc. That a type with more than 20 rows might be isolated by selection from a family like 1140 seems probable, but the possibility can be tested only by further breeding.

Table 3.—*Frequency distribution of number of rows per ear in cross (5x6).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear								
			8	10	12	14	16	18	20	22	24
No. 5 flint (2 yrs.)	P	8	289	2	2						
No. 6 dent	P	18	......	..	6	31	51	18	4		
No. 5x6	F_1	8	13	36	53	10					
(5x6)-1	F_2	12	12	48	35	9	1				
(5x6)-2	F_2	10	7	22	15	2					
(5x6)-22	F_2	10	8	45	31	1					
(5x6)-23	F_2	12	4	25	60	18	4	2	1		

Table 4.—*Frequency distribution of number of rows per ear in cross (5x2).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear								
			8	10	12	14	16	18	20	22	24
No. 5 flint (2 yrs.)	P	8	289	2	2						
No. 2 dent	P	16	...	..	2	14	56	42	20	1	1
No. 5x2	F_1	8	1	9	20	4					
(5x2)-6	F_2	10	4	18	61	14	3	1			

Table 5.—*Frequency distribution of number of rows per ear in cross (11x5).*

Designation	Gen.	Rows of parent	Classes for number of rows per ear								
			8	10	12	14	16	18	20	22	24
No. 11 flint	P	12	1	4	387	7	1				
No. 5 flint	P	8	280	2	2						
No. 11x5	F_1	12	2	11	26	2					
(11x5)-8	F_2	12	10	38	107	23	8				
(11x5)-18	F_2	10	19	33	100	5					

TABLE 6.—*Frequency distribution of number of rows per ear in cross (11x18).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear								
			8	10	12	14	16	18	20	22	24
No. 11 flint	P	12	1	4	387	7	1				
No. 18 sugar (2 yrs.)	P	12	13	32	51	4					
No. 11x18	F_1	12	2	10	24	1	1				
11x18)-4	F_2	12	1	9	78	10					
11x18)-10	F_2	10	8	13	62	13					

TABLE 7.—*Frequency distribution of number of rows per ear in cross (15x8).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear								
			8	10	12	14	16	18	20	22	24
No. 15 flint	P	8	100	1							
No. 8 dent	P	14	...	3	54	36	12	2			
No. 15x18	F_1	8	1	2	5	1					
(15x8)-2	F_2	10	14	15	28	9	1				
(15x8)-3	F_2	12	4	13	25	6	3				
(15x8)-2-10	F_3	14	...	1	8	14	6	1	1		
15x8)-2-1	F_3	8	32	35	23	4					
15x8)-2-5	F_3	12	4	41	116	15	3	1			

TABLE 8.—*Frequency distribution of number of rows per ear in cross (8x54).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear								
			8	10	12	14	16	18	20	22	24
No. 8 dent	P	12	..	3	54	36	12	2			
No. 54 sugar	P	8	89	25	7						
No. 8x54	F_1	12	1	6	14						
(8x54)-1	F_2	12	9	22	16	1					
(8x54)-5	F_2	12	1	3	16	1					
(8x54)-1-1	F_3	10	..	15	87	4					
(8x54)-1-2	F_3	8	20	38	50						
(8x54)-1-2a	F_3	10	61	48	54						
(8x54)-1-3	F_3	10	32	75	15						
(8x54)-1-3a	F_3	8	5	20	27	1					
(8x54)-1-5	F_3	12	..	33	158	26	3				
(8x54)-1-6	F_3	12	4	36	109	8	2				
(8x54)-1-10	F_3	8	Very irregular, mostly 8-rowed								
(8x54)-1-13	F_3	10	96	43	8						

TABLE 9.—*Frequency distribution of number of rows per ear in cross (60-3x54).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear						
			8	10	12	14	16	18	20
60	P	12	1	13	11	1	1		
54	P	8	25	2	1				
(60-3x54)	F_1	10	8	10	12	2	1		
(60-3x54)-1	F_2	16	..	..	4	8	5		
(60-3x54)-5	F_2	12	7	8	14	2	1		
(60-3x54)-6	F_2	12	5	11	8				
(60-3x54)-1-1AS	F_3	12	1	6	23	40	29		
(60-3x54)-1-1EO	F_3	16	..	..	15	16	25	6	1
(60-3x54)-1-5	F_3	16	2	10	38	21	10		
(60-3x54)-1-7	F_3	12	2	30	90	40	12		
(60-3x54)-5-1	F_3	12	10	22	44	10			
(60-3x54)-5-2	F_3	10	4	7	15	2	1		
(60-3x54)-5-3	F_3	8	42	73	25				
(60-3x55)-6-1	F_3	10	23	29	15	2			
(60-3x54)-6-5	F_3	10	55	33	6				

TABLE 10.—*Frequency distribution of number of rows per ear in cross (60-5x54).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear						
			8	10	12	14	16	18	20
60	P	12	1	13	11	1	1		
54	P	8	25	2	1				
(60-5x54)	F_1	12	2	6	54	7	1		
(60-5x54)-2	F_2	12	2	7	6	1			
(60-5x54)-6	F_2	14	0	1	10	2			
(60-5x54)-8	F_2	12	3	13	4				
(60-5x54)-11	F_2	10	14	14					
(60-5x54)-12	F_2	12	1	4	14	10	2		
(60-5x54)-2-3CS	F_3	8	46	20	4				
(60-5x54)-11-2CS	F_3	10	43	44	14	1			
(60-5x54)-11-3AS	F_3	10	56	10					
(60-5x54)-11-5AS	F_3	8	65	26	1				
(60-5x54)-11-5CS	F_3	10	50	24	7				
(60-5x54)-11-10AS	F_3	8	71	33	10				
(60-5x54)-12-1ES	F_3	12	12	34	51	28	20	6	2
(60-5x54)-12-2ES	F_3	12	13	44	62	28	2		

TABLE 11.—*Frequency distribution of number of rows per ear in cross (60-8x54).*

Designation	Gen.	Rows of parents	Classes for number of rows per ear						
			8	10	12	14	16	18	20
60	P	12	1	13	11	1	1		
54	P	8	25	2	1				
(60-8x54)	F_1	10	3	5	2	1			
(60-8x54)-1	F_2	10	20	3					
(60-8x54)-8	F_2	14	2	2	14	10			
(60-8x54)-1-1ES	F_3	8	61	10	1	1			
(60-8x54)-8-8CS	F_3	14	20	43	53	7	1		

Table 12.—*Frequency distribution of number of rows per ear in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Rows of parents	Classes for number of rows per ear: 8	10	12	14	16	18	20	22	24	26	28	Mean
Missouri dent	......	P	....	...	....	1	1	7	9	6	1	....	....	....	17.7 (?)
Tom Thumb pop	......	P	....	....	2	15	3	....	....	...	...	...	....	..	11.4 (?)
F_1 generation	......	F_1	....	....	....		.	2	2	1	....	.	....	...	(?)
510	1910	F_2	....	1	2	16	36	54	31	21	9	1	....	....	16.30±.15
1127	1911	F_2	....	....	1	13	26	15	6	2	...	....	...	....	14.57±.18
1128	1911	F_2	....		....	3	8	15	19	15	1	2		...	17.46±.22
1142	1911	F_3	12	1	7	46	17	3	....	...		...	....	...	12.38±.11
1132	1911	F_3	16	....	2	15	7	5	3	....	...		...	..	13.50±.26
1144	1911	F_3	14	....	1	15	29	33	3	..	...	....	....	...	14.54±.13
1134	1911	F_3	18	....	...	13	19	10	1	....	....	....	....	...	13.95±.16
* 1150	1911	F_3	18	...	....	8	15	14	1	1	....	...	.	....	14.56±.20
1131	1911	F_3	20	....	..	6	16	21	4	3	.	....	....	...	15.28±.19
* 1147	1911	F_3	20	...		9	22	19	11	2	1	.	....	....	15.31±.19
1133	1911	F_3	12	...	....	5	13	22	8	2	....	...	....	...	15.56±.18
1143	1911	F_3	14	..	....	3	15	28	14	1	....	...	....	....	15.84±.15
1145	1911	F_3	18	....	...	4	15	32	8	6	....	...	....	....	15.91±.17
1146	1911	F_3	14	....	...	3	26	28	22	5	....	..		....	16.00±.14
1149	1911	F_3	16	....	....	4	16	26	5	6	....	...	...	..	15.75±.18
1138	1911	F_3	18	....	..	3	12	33	20	8	2	..	....	...	16.62±.16
1139	1911	F_3	16	...	.	3	10	23	26	13	7	....	....	....	17.39±.18
1135	1911	F_3	16	..	....	5	13	16	18	8	3	4	....	..	17.07±.25
1137	1911	F_3	18	...	....	..	4	11	9	16	12	1	....	...	18.90±.24
1141	1911	F_3	20	....	...	...	2	17	16	20	8	4	1	....	18.91±.21
1140	1911	F_3	20	....		....	....	1	10	31	20	9	3	1	21.04±.17

*The brace indicates that the families joined by it are duplicates grown in different parts of the field from seed of the same ear.

INHERITANCE OF LENGTH OF EARS.

Length of the ear of maize is perhaps as good a character complex for inheritance studies as is found in the species. It is not affected by heterozygosis to as great a degree as height, altho some effect may be traced. Like other size characters, length of ear is intimately connected in development and in heredity with other complexes, yet it is not so markedly affected by external conditions as the height of plant. This statement. however, must be considered as somewhat tentative. Length of ear may be greatly changed by external conditions, yet if soil

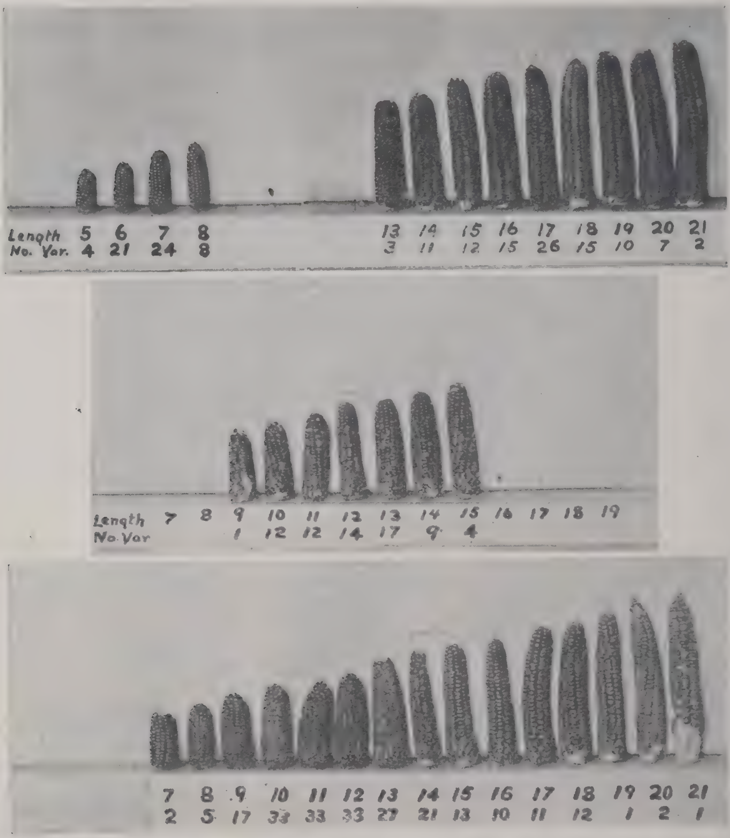
Length 5 6 7 8 13 14 15 16 17 18 19 20 21
No. Var. 4 21 24 8 3 11 12 15 26 15 10 7 2
Length 7 8 9 10 11 12 13 14 15 16 17 18 19
No. Var 1 12 12 14 17 9 4
7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
2 5 17 33 33 33 27 21 13 10 11 12 1 2 1

Fig. 1. Size of ears of Tom Thumb pop and Black Mexican sweet (top row), the F_1 generation of the cross between these varieties (middle row), and the F_2 generation of the same cross (bottom row),—1-9 natural size.

and moisture conditions are as uniform as is possible in field experiments and if these conditions are suitable for normal development, unavoidable changes in meteorological conditions do not change the ear development to any great extent. The greatest changes occur thru physiological correlation. Number of rows of seeds, and therefore total number of seeds, is inversely correlated with ear length. Size of seed and possibly the character of the seed may also have some effect, tho just what this effect is we are not prepared to say. Size of plant is directly correlated with length of ear.

How much of these correlations is gametic in the sense of true gametic couplings is unknown. It is apparently physiological in most cases, tho this physiological correlation is imposed by gametic constitution. In other words, a plant which is gametically large and a plant that is gametically small have different possibilities of ear development even when the same genes immediately affecting ear development are present. Expressed in genetic language, zygote (tall + ear length *AABBCC*) gives longer ears than zygote (short + ear length *AABBCC*).

Tables 13, 14, and 15 give the data on lengths of ear for the crosses (60-3x54), (60-5x54), and (60-8x54). These, it will be remembered, are three crosses made between individual plants of Tom Thumb pop (No. 60) and Black Mexican sweet (No. 54).

Unfortunately the data on the F_1 generations were taken only for the cross (60-5x54). It can be stated definitely that the range of variability in the other two families was no greater, but not that the percentage of variability was no greater. It is possible that a slight error is introduced, therefore, in comparing the F_2 generations of the crosses (60-3x54) and (60-8x54) with the F_1 data taken for cross (60-5x54). From what is known of the F_1 generations, however, it is thought that the error is very small.

In cross (60-3x54), three F_2 families were grown from selfed ears of the F_1 generation. If 12.48 ± .72 per cent represents the correct variability of the F_1 generation (Table 13), then the variability of each F_2 generation is much greater, namely, 16.70 ± .67 per cent, 15.87 ± .63 per cent, and 15.54 ± .90 per cent respectively. Perhaps it is wrong to compare the variability of the total population in F_2 with that of F_1, for the F_1 ears followed to the F_2 generation may have had different gametic formulae. The figures 22.30 ± .74 per cent are simply given for what they are worth. There is no way of disregarding the fact that one F_2 family, (60-3x54)-1, had a greater range of variability than F_1 by *five* classes. Individuals were obtained, therefore, that were exactly like typical individuals of both of the parental varieties.

Let us see how these individuals behaved in the F_3 generation.

Disregarding the progeny of ear (60-3x54)5-2CO because there were only 29 individuals, there is a range of variability from 12.66 ± .68 per cent to 19.61 ± .98 per cent. There is no question then but that the progenies of different F_2 ears show great deviations in variability of ear length, as should be expected if segregation of multiple factors occurs. The most interesting fact, however, is the differences in mean length of ear shown by the various frequency distributions of F_3. The mean length of the progeny of ear (60-3x54)6-5EO is only 9.7 ± .11 cm. They compare very favorably with Tom Thumb pop, the smaller parent, tho they are sweet segregates breeding true. Perhaps here again extremely small segregates are less common than they should be theoretically on account of the slight increase in size due to heterozygosis. Perhaps also the *combination of genes representing other character complexes* that would be most favorable to small size was not obtained.

On the other hand, the progeny of ear (60-3x54)1-7ES average 15.9 ± .15 cm. They have nearly the same length as the long-eared parent, Black Mexican. They average about twelve rows per ear, and are starchy segregates, however, so perhaps they are not as long as they would be with the same zygotic structure for ear size, if they were typically 8-rowed and wrinkled like the Black Mexican. At least there is good reason for suspecting a physiological correlation between long ears and few rows per ear.

Cross (60-5x54), Table 14, does not show such uniform increase in variability in F_2 over that shown by F_1 as does the cross just described. There is an increased range of variability and an increase in the calculated coefficient of variability in each of the five F_2 families grown, but in three cases out of five this increase is not significant. If one adds together the entries in all of the five families, he obtains a frequency distribution with a coefficient of variability of 15.67 ± .30 per cent. This coefficient is considerably larger than that of F_1, 12.48 ± .72 per cent, but the procedure is questionable.

The nine F_3 families grown show great range in variability. The smallest coefficient is 10.46 ± .60 per cent and the largest coefficient 21.68 ± .88 per cent. It is unfortunate that no extremely short ears and but one extremely long ear were selfed, but this should not be regarded as the fault of the experimenter. When the ear is bagged for selfing, one is unable to tell whether it will be large or small. Over 300 ears were selfed in the F_2 generation and of these about 275 matured, but among them were found but one normal ear of 7 cm. and but one ear of 18 cm. Mice destroyed the short ear, and recourse to ears 9 cm. and 10 cm. in length was necessary. The average of the progeny of

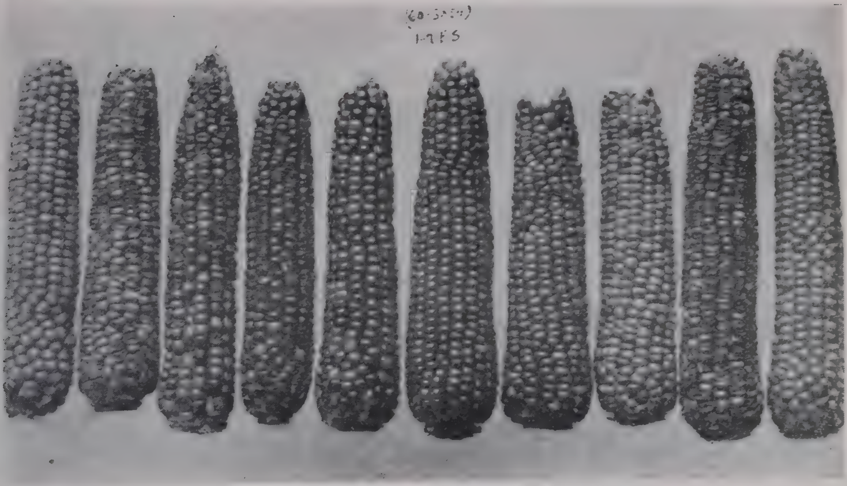

Fig. 2. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

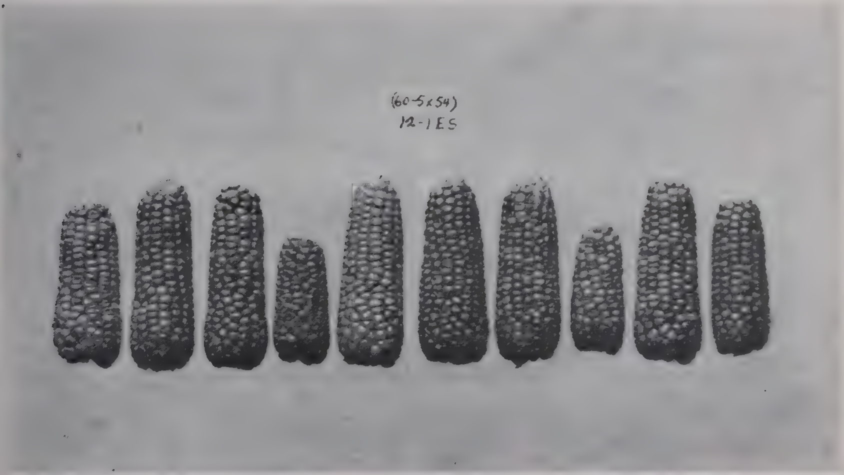

Fig. 3. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

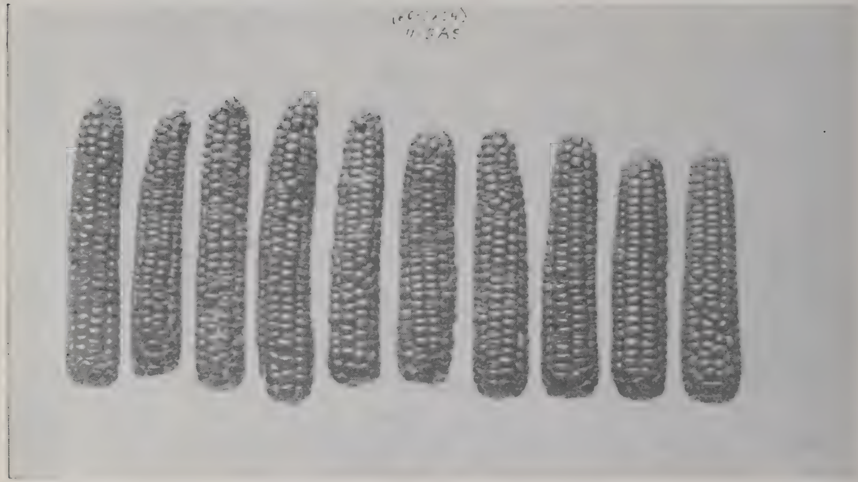

Fig. 4. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

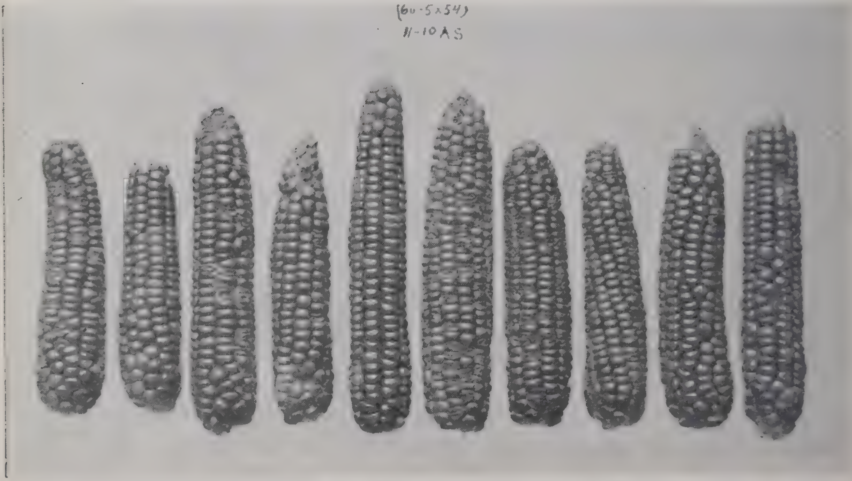

Fig. 5. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

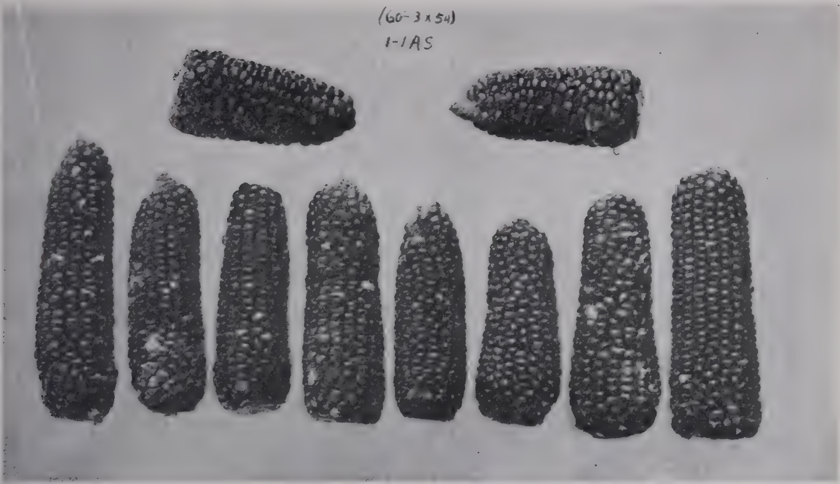

Fig. 6. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

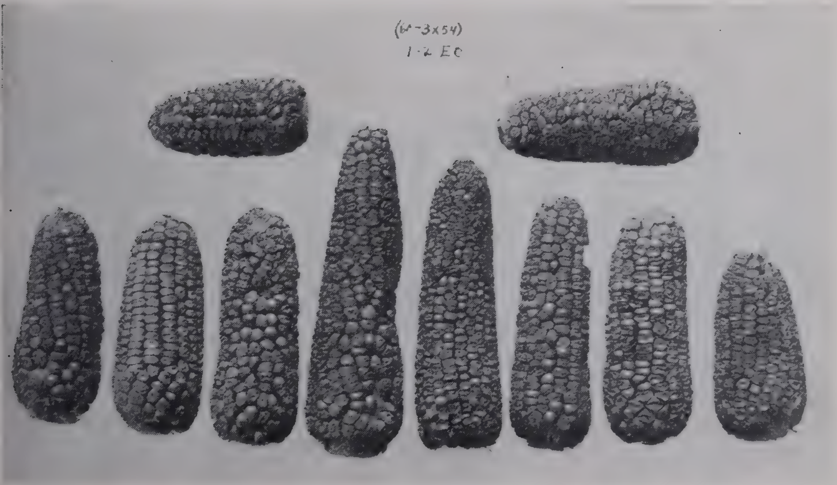

Fig. 7. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

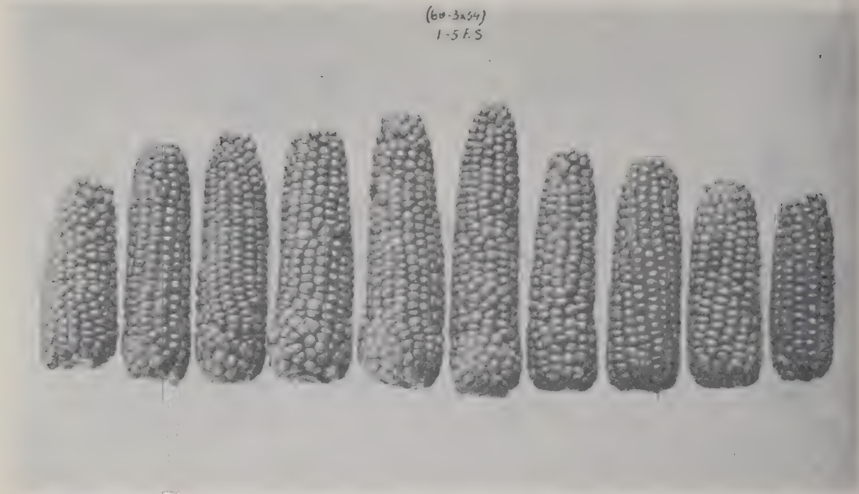

Fig. 8. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

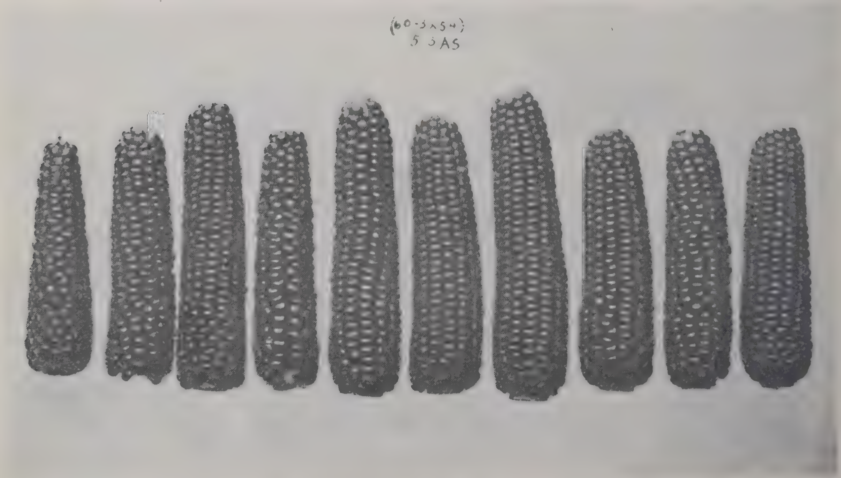

Fig. 9. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

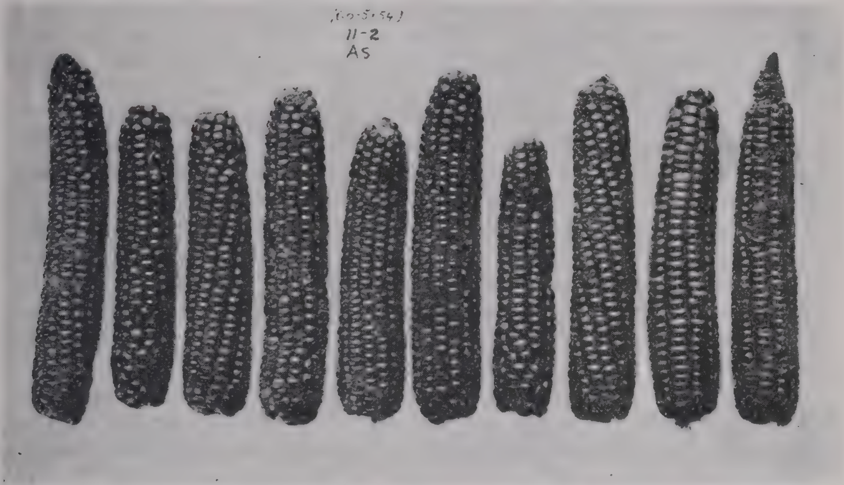

Fig. 10. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

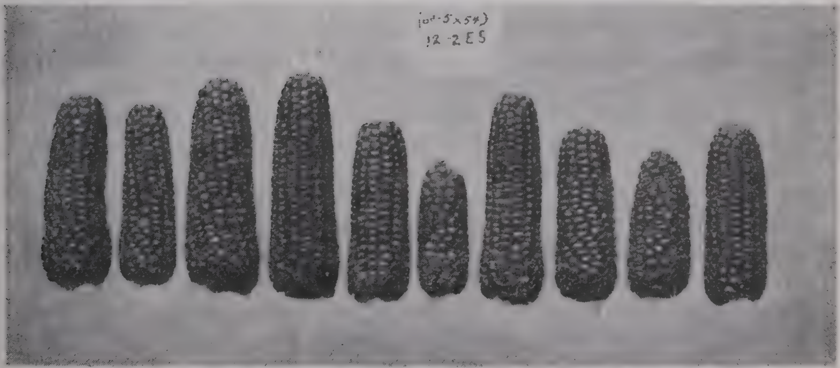

Fig. 11. Representative ears of an F_3 generation of a cross between Tom Thumb pop and Black Mexican sweet—2-9 natural size.

ear (60-5x54)12-1ES, which was itself 9 cm. long, was 10.0 ± .12 cm. The average of the progeny of ear (60-5x54)-12-2ES, an ear of 9 cm. long, was 9.2 ± .07. These families of short ears contrast noticeably with the family produced by ear (60-5x54)-11-2AS an ear 18 cm. long, for this family averaged 15.8 ± .13 cm. In fact, the extreme variates of the shortest family and the longest family scarcely overlap.

Cross (60-8x54) is notable for the extreme variability of F_2. Two families were grown, in which the coefficients of variability were 14.80 ± .69 per cent and 18.95 ± .89 per cent respectively. The total number of F_2 individuals gave a coefficient of variability of 17.44 ± .41 per cent. It happened that no long F_2 ears were selfed in this cross. Two medium length ears were grown primarily for other purposes, however, and their progeny measured. One family was very short, averaging 9.3 ± .07 cm. and the other family very variable, showing a coefficient of variability of 21.52 ± 1.23.

The data for ear length in the cross of Tom Thumb with Missouri dent are given in Table 16. As in the case of number of rows, the parents and F_1 are represented by measurements taken from ears kept for samples. The records of the F_1 generation grown in 1910 were accidently destroyed and no F_1 was grown in 1911. The Missouri dent, owing to its lateness of maturity, did not ripen in 1911 and Tom Thumb produced few ears that year. As a matter of fact the samples preserved represent the parents and F_1 fairly well. The F_1 ears as a whole were practically as long as those of Missouri dent. The F_2 families differed in ear length as they did in other characters to be noted later. The parent stocks evidently were heterozygous in some factors influencing ear length. None of the F_2 ears were as short as the average Tom Thumb pop ear but many were shorter than any ears of Missouri dent or of the F_1 generation. The F_3 families, all of which came from a single F_2 family and therefore, from a single F_1 ear, differed noticeably in ear length. The shortest average length was a little over 10 centimeters and the longest a little over 18 centimeters. The longest ears of some families were only slightly longer than the shortest ears of other families. It seems probable that types of ear length like the parent types as well as various intermediate types could readily be established from this material.

Table 17 includes all available data in regard to ear length from the cross of California pop with Missouri dent. F_1 families 502 and 505 were grown under fairly favorable weather conditions in 1910, while all the other families listed were grown under the conditions of extreme drouth prevailing at Lincoln, Nebraska, in 1911. The general appearance of the Missouri dent plants, No. 833, indicated that they suffered more seriously from the dry weather than did the California pop plants. Many of the Missouri dent plants produced no ears and a considerable number of the ears produced were little better than "nubbins." The F_1 plants, families 836 and 837, were apparently much less seriously affected by the unfavorable weather than any of the other lots, which doubtless, in part at least, accounts for the fact that their ears averaged quite as long as the ears of the Missouri dent parent. The mean ear lengths of the F_2 families were distinctly intermediate between the means of the parents. Altho the range of variation in the F_2 families was not extreme, the variability in F_2, as measured by the coefficient of variation, was in general considerably greater than that of the F_1 families.

TABLE 13.—*Frequency distribution of lengths of ears in cross (60-3x54).*

Designation	Gen.	Parent class	Class centers in cm. for lengths of ears																	Mean	Coef. var.
			5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21		
60	P	......	4	21	24	8	......	......	......	......	......	......	......	......	......	......	......	......	......	6.6 ± .07	12.27 ± .78
54	P	......	......	......	......	......	......	......	......	......	3	11	12	15	26	15	10	7	2	16.8 ± .12	11.13 ± .53
(60-5x54)	F_1	......	......	......	......	......	1	12	12	14	17	9	4	......	......	......	......	......	......	12.1 ± .12	12.48 ± .72
(60-3x54)-1	F_2	......	......	......	1	4	10	11	24	27	26	27	12	6	2	1	......	......	......	12.4 ± .11	16.70 ± .67
(60-3x54)-5	F_2	......	......	......	......	......	5	9	9	29	28	33	26	18	13	8	1	......	......	13.8 ± .11	15.87 ± .63
(60-3x54)-6	F_2	......	......	......	......	6	4	6	14	17	14	8	1	1	......	......	......	......	......	11.7 ± .26	15.54 ± .90
(60-3x54)-total	F_2	......	......	......	1	10	19	26	47	73	68	68	39	25	15	9	1	......	......	12.6 ± .13	22.30 ± .74
(60-3x54)-1-1AS	F_3	11	......	......	4	3	13	13	18	23	9	5	4	3	3	1	......	......	......	11.4 ± .15	19.61 ± .98
(60-3x54)-1-1EO	F_3	14	......	......	......	......	3	8	14	13	16	8	1	......	......	......	......	......	......	11.9 ± .12	12.06 ± .74
(60-3x54)-1-2AS	F_3	11	......	......	......	2	5	6	6	11	13	15	11	9	2	......	......	......	......	13.0 ± .17	16.99 ± .93
(60-3x54)-1-5ES	F_3	10	......	......	......	4	6	16	20	16	11	5	3	......	......	......	......	......	......	11.3 ± .12	14.68 ± .79
(60-3x54)-1-7ES	F_3	18	......	......	......	......	......	6	9	10	8	18	14	26	24	28	12	10	4	15.9 ± .15	17.87 ± .68
(60-3x54)-5-1BO	F_3	8	......	......	......	......	1	8	5	13	10	18	18	11	2	2	......	......	......	13.6 ± .14	14.77 ± .77
(60-3x54)-5-2CO	F_3	7	......	......	......	1	......	7	10	7	4	......	......	......	......	......	......	......	......	11.2 ± .14	9.94 ± .89
(60-3x54)-5-3AS	F_3	12	......	2	3	3	17	16	19	25	26	17	7	4	......	2	......	......	......	11.8 ± .13	14.27 ± .59
(60-3x54)-6-1ES	F_3	10	......	1	......	14	15	24	10	2	2	1	......	......	......	......	......	......	......	9.7 ± .11	14.37 ± .84
(60-3x54)-6-5EO	F_3	11	......	......	2	3	4	14	19	26	19	7	......	......	......	......	......	......	......	11.5 ± .11	13.66 ± .68

TABLE 14.—*Frequency distribution of lengths of ears in cross (60-5x54).*

Designation	Gen.	Parent class	Class centers in cm. for lengths of ears																	Mean	Coef. var.
			5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21		
60	P		4	21	24	8														6.6 ± .07	12.27 ± .78
54	P										3	11	12	15	26	15	10	7	2	16.8 ± .12	11.13 ± .53
(60-5x54)	F_1						1	12	12	14	17	9	4							12.1 ± .12	12.48 ± .72
(60-5x54)-2	F_2						1	5	8	27	32	31	28	13	5	2				13.6 ± .16	12.70 ± .50
(60-5x54)-6	F_2				1	2	6	9	22	43	24	14	11		3	3	1			12.4 ± .11	16.22 ± .67
(60-5x54)-8	F_2				1	2	3	8	9	17	19	14	10	7	7	1				13.0 ± .16	17.60 ± .87
(60-5x54)-11	F_2						3	5	7	15	21	19	10	6	2					13.1 ± .13	13.59 ± .70
(60-5x54)-12	F_2				2	1	9	29	34	43	36	13	4	1						11.7 ± .08	13.36 ± .49
(60-5x54)-total	F_2				4	5	22	56	80	145	129	91	63	27	17	6	1			12.7 ± .06	15.67 ± .30
(60-5x54)-2-3AS	F_3	11					1	5	8	9	25	20	2							12.7 ± .11	10.46 ± .60
(60-5x54)-11-2AS	F_3	18								9	7	13	18	25	20	6	4			15.8 ± .13	12.56 ± .57
(60-5x54)-11-2CS	F_3	10		1		8	22	25	15	22	7	2								10.5 ± .10	14.92 ± .72
(60-5x54)-11-3AS	F_3	12			1	1	3	6	10	6	17	12	7	3						12.5 ± .17	15.89 ± .96
(60-5x54)-11-5AS	F_3	12				1	1	3	9	17	28	14	13	5	1					13.1 ± .12	12.62 ± .64
(60-5x54)-11-5CS	F_3	10		1	1	1	9	18	16	13	16	5	1							11.2 ± .13	15.36 ± .83
(60-5x54)-11-10AS	F_3	10					4	1	6	11	24	18	17	16	11	4	1	1		14.2 ± .14	15.23 ± .70
(60-5x54)-12-1ES	F_3	9		5	13	20	28	28	30	10	7	6	3	2	1					10.0 ± .12	21.68 ± .88
(60-5x54)-12-2ES	F_3	10		3	10	33	47	40	18	3										9.2 ± .07	13.55 ± .53

TABLE 15.—*Frequency distribution of lengths of ears in cross (60-8x54).*

Designation	Gen.	Parent class	Class centers in cm. for lengths of ears																	Mean	Coef. var.
			5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21		
60	P		4	21	24	8														6.6 ± .07	12.27 ± .78
54	P										3	11	12	15	26	15	10	7	2	16.8 ± .12	11.13 ± .53
(60-5x54)	F_1						1	12	12	14	17	9	4							12.1 ± .12	12.48 ± .72
(60-8x54)-1	F_2					2	4	1	7	17	16	17	10	10	11	12	1	2	1	14.3 ± .17	18.95 ± .89
(60-8x54)-8	F_2				2	3	13	32	26	16	11	4	3							10.9 ± .10	14.80 ± .69
(60-8x54)-total	F_2				2	5	17	33	33	33	27	21	13	10	11	12	1	2	1	12.9 ± .08	17.44 ± .41
(60-8x54)-1-1ES	F_3	12		3	4	1	2	3	3	6	11	19	12	6	3					12.9 ± .22	21.52 ± 1.23
(60-8x54)-8-8CS	F_3	11		5	3	19	42	39	14	2										9.3 ± .07	13.16 ± .57

TABLE 16.—*Frequency distribution of length of ear in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Parent class	Class centers in centimeters for length of ears																					Mean
				5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
Missouri dent		P										1	4	4	5	3	4	2	2	1					16.6 (?)
Tom Thumb pop		P		1	1	5	6	3	2																7.8 (?)
F1 generation		F1													1			2	1	1					(?)
510	1910	F2				4	3		2	8	14	14	19	34	34	20	18	11	5		1	1			15.15 ± .14
1127	1911	F2								1	2	3	3	5	7	9	11	11	6	2	1		1	1	17.40 ± .23
1128	1911	F2							2	1	1	5	6	5	6	9	11	10	2	4	1				16.66 ± .23
1132	1911	F3	13		5	1	1	3	5	4	8	2	2	1											10.34 ± .30
* 1150	1911	F3	16		2	1	1		2	1	2	5	10	6	3	3	2	1							13.62 ± .33
* 1134	1911	F3	16				2	2	1	5	4	4	7	6	3	5	2	2							13.81 ± .29
1140	1911	F3	11				1		3	8	8	19	12	13	6	2	2	1							13.56 ± .16
1133	1911	F3	12				1	1	3	9	3	14	11	5	3										12.82 ± .17
1137	1911	F3	13					1	2	4	4	12	20	8	2										13.38 ± .14
1135	1911	F3	14				1		1		2	5	12	6	8	11	12	6	3						15.97 ± .20
1143	1911	F3	14							2	5	7	13	12	15	6	1								14.67 ± .14
1141	1911	F3	16						1	2	3	4	4	14	12	14	10	4							15.76 ± .17
1149	1911	F3	16							1	3	4	13	8	7	8	8	2	1	1		1			15.70 ± .21
* 1147	1911	F3	17							1	1	1	3	3	11	14	15	10	4		1				17.17 ± .16
* 1131	1911	F3	17									1	3	2	5	7	10	8	7	4	2	1			18.14 ± .21
1138	1911	F3	17								1	2	5	8	12	15	12	8	10	2	3				17.32 ± ,17
1142	1911	F3	17								1	3	5	9	21	12	14	4	4	1					16.55 ± .14
1144	1911	F3	15								1	2	4	6	15	21	16	10	4	2					17.05 ± .13
1139	1911	F3	20								1	5	4	5	16	16	15	12	3	4	1				17.07 ± .16
1145	1911	F3	19									6	8	7	21	12	6	2	2	1					16.03 ± .15
1146	1911	F3	17										6	10	9	13	16	12	10	4	3		1		17.73 ± .16

* Duplicates.

TABLE 17.—*Frequency distribution of length of ears in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Class centers in centimeters for length of ears																	Mean	Coef. var.
			4.25	5.25	6.25	7.25	8.25	9.25	10.25	11.25	12.25	13.25	14.25	15.25	16.25	17.25	18.25	19.25	20.25		
834	1911	P	3	10	21	5	....	....	....	....	....	....	....	....	....	....	....	....	....	5.97 ± .09	13.13 ± 1.02
835	1911	P	5	17	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	5.21 ± .08	11.25 ± 1.08
833	1911	P	....	....	....	....	....	2	1	2	1	1	6	1	3	2	2	1	1	14.64 ± .42	20.61 ± 2.14
836	1911	F_1	....	....	....	....	....	1	...	...	...	4	6	13	8	3	2	....	....	15.25 ± .18	10.56 ± .84
837	1911	F_1	....	....	....	....	....	....	1	1	2	1	8	5	3	6	1	1	....	15.15 ± .26	13.58 ± 1.23
829	1911	F_2	....	....	1	6	3	7	11	12	9	7	4	3	....	....	....	....	....	11.00 ± .19	20.00 ± 1.26
830	1911	F_2	....	....	1	5	4	4	8	7	10	4	3	....	....	....	....	....	....	10.68 ± .21	19.67 ± 1.44
831	1911	F_2	2	1	2	7	3	4	6	10	3	8	2	1	....	....	....	....	....	10.19 ± .26	26.55 ± 1.94
832	1911	F_2	....	1	...	2	8	6	8	6	9	8	6	1	....	....	....	....	....	11.05 ± .21	20.44 ± 1.38
839	1911	F_2	....	....	....	....	2	3	8	7	14	8	4	2	....	....	....	....	....	11.88 ± .16	14.03 ± 1.00
840	1911	F_2	....	....	1	2	3	10	13	10	7	8	5	1	....	....	....	....	....	11.03 ± .17	17.91 ± 1.14

INHERITANCE OF DIAMETER OF EARS.

Diameter of ear is directly correlated with number of rows and with seed size and probably also, negatively, with length of ear. In general, ears show less fluctuation in diameter than they do in length.

Table 18 exhibits the data obtained from the cross of California pop and Missouri dent. As grown in 1911, the former, Nos. 834 and 839, had a mean ear diameter of a little less than 25 millimeters and the latter, No. 833, a mean diameter of a little over 50 millimeters. The mean diameter of F_1 ears grown the same year, Nos. 836 and 837, was nearly 42 millimeters, or about 4 millimeters greater than the mid-parental value. It seems likely that this small increase over the mid-parental diameter is due to the increased vigor accompanying heterozygosis, for the mean diameters of the F_2 families averaged only a little over 37 millimeters, or almost exactly half way between the parents. The F_1 families grown under the more favorable conditions of 1910, Nos. 502 and 503, naturally had somewhat greater ear diameters than the F_1 families of 1911.

The ranges of variation of the F_2 families were not great, having extended only from a little above the mean of California pop to a little below the mean of Missouri dent. While the number of individuals of no one F_2 family was large, the total number of individuals of the six F_2 families was 321, or more than a sufficient number to give an even chance of obtaining all possible combinations of factors if the parents differed by only four factors. It is probable, however, that neither the seed size nor the number of rows of the parents differed by so few as two factors and, since diameter of ears is directly related to both of these other ear characters, it would not be strange if the difference in diameter of ears between Missouri dent and California pop were due to as many as seven or eight factors. In the latter case, something like 65,000 F_2 individuals would have to be grown to afford an even chance of obtaining a single plant each, gametically like the two parent types as regards factors influencing diameter of ears. In this case, some of the smallest and some of the largest F_2 ears of the 321 should prove heterozygous for diameter factors and should, therefore, produce F_3 plants more extreme than any plants of F_2.

This apparently is exactly what happened in case of the cross of Missouri dent with Tom Thumb pop, the data for which are presented in Table 19. Several of the F_3 families contained individuals with ears of smaller diameter than any F_2 ear. In fact the mean diameter of No. 1132 was practically equal to the diameter of the smallest ears of the F_2 families grown the same year, Nos. 1127 and 1128, and also equal to the particular F_2 ear from which it came. Whether types with still smaller ears can be isolated by selection from family 1132 remains to be seen.

Many of the F_3 families of this cross were distinctly different from others in ear diameter. There were six families, for instance, the smallest ears of which were larger than the largest ears of family 1132. The mean diameter varied from nearly 31 to nearly 46 millimeters.

TABLE 18.—*Frequency distribution of diameter of ears in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Class centers in millimeters for diameter of ears																		Mean	Coef. var.
			22.5	24.5	26.5	28.5	30.5	32.5	34.5	36.5	38.5	40.5	42.5	44.5	46.5	48.5	50.5	52.5	54.5	56.5		
833	1911	P	....	....	....	....	....	....	....	....	....	....	2	2	2	4	2	4	5	2	50.33 ± .60	8.46 ± .84
834	1911	P	8	20	8	2	1	....	....	....	....	....	....	....	....	....	....	....	....	....	24.86 ± .20	7.26 ± .55
835	1911	P	7	12	6	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	24.58 ± .21	6.57 ± .61
836	1911	F_1	....	....	....	....	....	1	2	2	2	4	15	7	3	1	....	....	....	....	41.91 ± .39	8.29 ± .65
837	1911	F_1	....	....	....	....	....	....	....	2	6	7	6	5	3	....	....	....	....	....	41.53 ± .36	6.88 ± .61
829	1911	F_2	....	....	....	1	....	5	5	15	8	15	5	6	3	....	....	....	....	....	38.82 ± .33	10.06 ± .61
830	1911	F_2	....	....	1	...	4	5	10	7	5	7	4	2	1	....	....	....	....	....	36.80 ± .43	11.77 ± .84
831	1911	F_2	....	....	....	3	9	7	8	12	7	2	1	....	....	....	....	....	....	....	34.58 ± .33	9.91 ± .68
832	1911	F_2	....	....	1	2	3	8	7	11	12	6	4	1	....	....	....	....	....	....	36.32 ± .36	10.77 ± .70
839	1911	F_2	....	....	....	....	....	5	1	10	8	9	8	4	3	....	....	....	....	....	39.42 ± .37	9.66 ± .67
840	1911	F_2	....	....	....	....	7	5	7	14	10	4	8	4	1	....	....	....	....	....	37.33 ± .37	11.29 ± .70

TABLE 19.- *Frequency distribution of diameter of ears in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Parent class	Class centers in millimeters for diameter of ears																						Mean	
				20.5	22.5	24.5	26.5	28.5	30.5	32.5	34.5	36.5	38.5	40.5	42.5	44.5	46.5	48.5	50.5	52.5	54.5	56.5	58.5	60.5	62.5		
Mo. dent		P															1	1	3	6	2		2	1		52.9 (1)	
Tom Thumb		P		4	5	6	3																			23.1 (1)	
F1 Generation		F_1											1	2	2											(1)	
510	1910	F_2																								37.31	22
1127	1911	F_2							1	4	4	2	8	9	7	11	8	4	4	1						42.09	14
1128	1911	F_2								3	3	5	7	10	9	5	13	3	3	2						42.37	14
1132	1911	F_3	30.5				5	5	7	11	4															30.75	30
1133	1911	F_3	32.5				1	3	7	17	12	6	2	2												33.18	28
1142	1911	F_3	32.5					4	7	16	20	21	4	2												34.31	21
1139	1911	F_3	34.5					1	2	10	22	28	11	6	2											35.94	20
1146	1911	F_3	34.5					1	2	3	17	21	19	17	3	1										37.29	22
*1134	1911	F_3	38.5					1	1	5	12	9	8	6	1											36.22	31
*1150	1911	F_3	38.5						1	2	6	10	9	4	6	1										37.83	35
1135	1911	F_3	38.5						1	3	7	17	15	10	7	3	4									38.65	30
1137	1911	F_3	36.5						2	4	6	14	9	11	6	1										37.74	30
1141	1911	F_3	36.5							9	6	23	22	7	1											36.94	20
1138	1911	F_3	38.5								3	1	13	18	19	17	1	2	1							41.50	21
1144	1911	F_3	40.5								1	1	7	13	23	22	10	3	1							43.02	21
1140	1911	F_3	40.5									3	8	18	18	20	7	1								42.31	21
1145	1911	F_3	42.5									1	8	17	22	10	6	1								42.16	21
*1147	1911	F_3	44.5									1	4	14	21	11	9	3	1							43.03	21
*1151	1911	F_3	44.5										5	9	12	15	7	1	1							43.18	26
1143	1911	F_3	42.5										4	9	13	13	11	4	7							44.10	29
1149	1911	F_3	44.5										2	3	7	14	18	5	5	3						45.76	29

* Duplicates.

[1] Measurements were taken in tenth-inches. The frequency distribution from 1.0 to 2.0 inches was 1, 4, 11, 21, 41, 17, 26, 19, 8, 0, 3.

INHERITANCE OF WEIGHT OF SEEDS.

The behavior of seed weight in the crosses (60-3x54), (60-5x54), and (60-8x54) may be considered together. The detailed data are shown in Tables 20, 21, and 22. In making the weights for this study, it was necessary to use a scheme by which the sugary or wrinkled seeds of the Black Mexican parent, No. 54, and of certain recessive segregates from the cross, could be weighed as starchy seeds. This end was accomplished by having starchy families growing near the wrinkled families. Crossed seeds which had become starchy thru xenia were usually obtained in sufficient numbers to make data upon 25 seeds possible. An insufficient number of hybrid starchy seeds, however, accounts for the meager data in certain families. It must be understood that this method of weighing is correct in theory, since the size of the seed is governed by the development of the pericarp and since this is unaffected by the pollen from a starchy race. The pericarp is merely filled out with starch by the dominance of starchiness in the F_1 endosperm.

In discussing these results, the weight of 25 seeds is taken as the unit quantity. When the mean weight of any particular family is stated, therefore, this is what is meant.

Tom Thumb No. 60 has an extremely small seed. The mean weight is 2.7 ± .03 grams. The mean weight of the Black Mexican is 8.3 ± .11 grams, but this is probably too high. These data were taken from plants raised from commercial seed, which was in a very mixed condition. The last three positive classes should probably be discarded for this reason. The ears upon which they were borne showed plainly that they had come from hybrid seed, —the male parent evidently being some large dent variety.

Small numbers in the frequency distributions of both parents and hybridity in the Black Mexican undoubtedly make the coefficients of variability—14.44 ± .90 per cent and 14.54 ± .96 per cent respectively—too high; but, even leaving this fact out of consideration, the ten F_2 families grown show increased variability over that of the F_1 generation in every case. The range of variability in each case overlaps that of the grandparents. The extreme F_2 individuals do not reach the extremes of either parent, but if one leaves out of account the three higher classes of the larger parent, for the reason given above, the extreme size of the Black Mexican is generally obtained. This may be a questionable procedure, but, as a matter of fact, the individuals used as the male parents of the crosses were only average in this character. The F_3 families often gave segregates with seeds as small as the smallest Tom Thumb seeds.

The F_3 families having the smallest mean seed weight were

(60-3x54)-6-1ES, (60-5x54)-2-3AS, and (60-5x54)-12-2ES, with means of 4.9 ± .08, 4.8 ± .07, and 4.6 ± .04 respectively. These means do not approach the mean of the Tom Thumb race very closely, yet the appearance of the families, is, as a whole, very like the Tom Thumb. Furthermore, the great difference in variability among the F_3 families, extending as it does from 13.90 ± .67 per cent to 24.96 ± 1.35 per cent, indicates a difference in heterozygosity from which we might well argue the ease of producing races like the original parental strains with a little more selection.

The family (60-5x54)-11-2AS, coming from a large segregate of F_2, gave a fraternity with a mean seed weight of 7.3 ± .08 grams. This is probably very close to the true mean seed weight of a well-selected Black Mexican race.

TABLE 20.—*Frequency distribution of weights of seeds in cross (60-3x54).*

Designation	Gen.	Parent class	Class centers in grams for weights of 25 seeds																				Mean	Coef. var.
			2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5		
60	P		7	22	28	4																	2.7 ± .03	14.44 ± .90
54	P										2	2	5	7	14	10	5	4	1	2	1	2	8.3 ± .11	14.54 ± .96
(60-5x54)	F_1					5	12	13	17	4	3												4.6 ± .06	13.91 ± .91
(60-3x54)-1	F_2					3	7	13	25	28	20	18	3	3		2							5.5 ± .06	16.94 ± .75
(60-3x54)-5	F_2						1	6	8	14	13	30	16	14	9	6	2	3					6.6 ± .07	17.67 ± .79
(60-3x54)-6	F_2					1	2	5	8	11	7	4	2	2									5.5 ± .09	16.15 ± 1.22
(60-3x54)-total	F_2					4	10	24	41	53	40	52	21	19	9	8	2	3					6.0 ± .05	19.50 ± .56
(60-3x54)-1-1AS	F_3	5.0			4	1	5	2	13	23	7	25	9	8			1	1					5.9 ± .08	20.40 ± 1.02
(60-3x54)-1-1EO	F_3	5.0 *			1		7	4	17	13	11	8	1		1								5.9 ± .07	14.97 ± .92
(60-3x54)-1-2AS	F_3	6.0	1		1		4		16	11	9	17	4	12	2	1		1					6.1 ± .09	20.50 ± 1.15
(60-3x54)-1-5ES	F_3	4.5			1		1	3	9	10	14	25	8	5	5								6.2 ± .06	13.92 ± .75
(60-3x54)-1-7ES	F_3	5.0					3	2	21	26	36	35	10	28	4	4							6.3 ± .05	15.31 ± .57
(60-3x54)-5-1BO	F_3	6.0 *	1		4	3	2	5	9	5	10	16	5	17	6	2	2	1					6.2 ± .11	24,96 ± 1.35
(60-3x54)-5-3AS	F_3	5.0			3	1	3	6	16	30	26	29	14	9	3	1							6.0 ± .06	16.81 ± .69
(60-3x54)-6-1ES	F_3	4.5	1		3	1	14	13	13	18	4	1	1										4.9 ± .08	20.99 ± 1.26
(60-3x54)-6-5EO	F_3	6.0 *				3	8	4	15	21	15	13	7	3	3	1							5.7 ± .07	17.31 ± .88

* Ear with wrinkled seeds. Weight estimated in terms of starchy seeds.

TABLE 21.—*Frequency distribution of weights of seeds in cross (60-5x54).*

Designation	Gen.	Parent class	Class centers in grams for weights of 25 seeds																				Mean	Coef. var.
			2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5		
60	P		7	22	28	4																	2.7 ± .03	14.44 ± .90
54	P										2	2	5	7	14	10	5	4	1	2	1	2	8.3 ± .11	14.54 ± .96
(60-5x54)	F_1					5	12	13	17	4	3												4.6 ± .06	13.91 ± 91
(60-5x54)-2	F_2				1	3	7	20	31	19	18	13	3	1									5.3 ± .05	16.10 ± .73
(60-5x54)-6	F_2			1	2	6	11	21	17	12	12	8	12	4	1								5.3 ± .08	22.54 ± 1.09
(60-5x54)-8	F_2					2	11	14	18	11	11	5	1										5.1 ± .06	15.98 ± .91
(60-5x54)-11	F_2				3	3	6	8	10	10	11	7	8	8	5	1		1					5.8 ± .11	24.48 ± 1.35
(60-5x54)-12	F_2				1	3	14	35	37	31	17	10	3		2								5.1 ± .04	14.40 ± .57
(60-5x54)-total	F_2			1	7	17	49	98	113	83	69	43	27	13	8	1		1					5.3 ± .03	20.56 ± .44
(60-5x54)-2-3AS	F_3	4.0	2				21	11	9	17	9		1										4.8 ± .07	18.67 ± 1.10
(60-5x54)-11-2AS	F_3	7.0					1		2	3	14	10	16	25	5	16	2	4	2	1			7.3 ± .08	15.94 ± .78
(60-5x54)-11-2CS	F_3	4.0					4	6	25	31	10	21	3	1	1								5.6 ± .05	13.90 ± .67
(60-5x54)-11-3AS	F_3	7.0					3	2	7	12	8	9	4	13	5	2		1					6.4 ± .09	17.43 ± 1.05
(60-5x54)-11-5AS	F_3	4.0				2	7	7	21	15	13	15	2	7	2								5.6 ± .07	18.29 ± .94
(60-5x54)-11-5CS	F_3	4.0			1	1	16	12	14	16	16	3	2										5.1 ± .06	16.50 ± .89
(60-5x54)-11-10AS	F_3	7.5					1	8	8	23	26	3	25	7	9	1	2		1				6.3 ± .07	17.94 ± .83
(60-5x54)-12-1ES	F_3	4.0			10	8	22	32	20	20	8	20	6	4	1	2							5.1 ± .07	24.06 ± .98
(60-5x54)-12-2ES	F_3	3.5		1	7	8	41	36	15	33	7	1											4.6 ± .04	17.25 ± .69

TABLE 22.—*Frequency distribution of weights of seeds in cross (60-8x54).*

Designation	Gen.	Parent class	Class centers in grams for weights of 25 seeds																				Mean	Coef. var.
			2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7 5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5		
60	P		7	22	28	4																	2.7 ± .03	14.44 ± .90
54	P										2	2	5	7	14	10	5	4	1	2	1	2	8.3 ± .11	14.54 ± .96
(60-5x54)	F_1					5	12	13	17	4	3												4.6 ± .06	13.91 ± .91
(60-8x54)-1	F_2						1	4	7	2	15	13	14	11	6	5							6.6 ± .08	16.39 ± .91
(60-8x54)-8	F_2					1	2	11	9	15	8	10	4	1	2	4	1						5.8 ± .10	20.93 ± 1.26
(60-8x54)-total	F_2					1	3	15	16	17	23	23	18	12	8	9	1						6.2 ± .07	19.84 ± .80
(60-8x54)-1-1ES	F_3	6.0					1		4	8	14	10	13	16	7								6.6 ± .07	13.73 ± .78
(60-8x54)-8-8CS	F_3	5.0	1		1	1	8	8	24	19	26	17	14	1	3								5.7 ± .06	17.99 ± .80

INHERITANCE OF BREADTH OF SEEDS.

In case of the crosses of California pop with Missouri dent and of the latter with Tom Thumb pop, the breadth of twenty-five kernels from an ear of each plant was determined. Tables 23 and 24 contain these data. Of the varieties of corn known to us, California pop has by far the smallest seeds. As grown in 1910 and 1911 (Table 23), the average breadth of twenty-five kernels of this variety was only about 85 millimeters, while the breadth of twenty-five Missouri dent kernels averaged about 216 millimeters. The F_1 seeds were distinctly intermediate in size. In 1910 the difference between the largest twenty-five seeds of California pop and the smallest class of F_1 was 20 millimeters and there was the same difference between the largest class of F_1 and the smallest of Missouri dent. In 1911 the F_1 families had somewhat larger seeds than in 1910. The variation in the F_2 families was noticeably greater than in the F_1 lots. The range of variation, however, was not sufficient in all the F_2 families together completely to close the gap between even the inner extremes of the parents. The greater variation in F_2 was doubtless due to a segregation of size factors, and types like the parents would probably have appeared had a sufficient number of F_2 plants been grown. How many F_2 plants it would be necessary to grow in order to have an even chance for the appearance of forms like the parents cannot be told. More than enough were grown to realize this result if the parents differed by only four factors influencing breadth of kernels. Obviously the difference between them must be considerably more than four factors. If they differ by five factors, over three times as many plants as were grown would have been necessary; if by six factors, nearly thirteen times as many; if by seven factors, over fifty times as many, and if by eight factors, over two hundred times as many. It is out of the question to grow in ordinary pedigree cultures any such number of individuals as would be necessary to regain the original types of seed size in F_2 if the parents differ by as many as seven or eight factors. But, by selecting F_2 plants with the smallest seeds and continuing the selection in F_3 and F_4, if necessary, it should be possible to regain the parent types in a few generations without growing excessively large numbers in any generation.

The F_3 families of the cross of Missouri dent with Tom Thumb pop (Table 24) illustrate the possibility of accomplishing this isolation gradually without growing extremely large numbers. True the parents of this cross did not differ so greatly in seed size as did Missouri dent and California pop and all the intervening classes were occupied by F_1 individuals. Furthermore the F_2 families taken together contained a few individuals with seeds smaller than the mean seed size of Tom Thumb pop and also a few with seeds larger than the mean seed size of Missouri dent. But none of the more than 300 F_2 plants had seed as small as the smallest of Tom Thumb pop or as large as the largest of Missouri dent, and neither one of the three F_2 families alone overlapped appreciably even the inner extremes of both parent varieties. F_2 family 510 with 188 plants represented in Table 24 had a few plants with seeds nearly as small as the mean seed size of Tom Thumb pop but none with seeds larger than the very smallest seed-size class of Missouri dent. From this one F_2 fraternity, the seven F_3 lots included in the table were grown. No F_3 family came from the large-seeded F_2 plants, so that very large-seeded F_3 lots were not to be expected. F_3 families 1139 and 1140 were the descendants of comparatively small-seeded, tho not the smallest seeded, plants of 510. Their mean seed sizes were slightly less than the seed size of their F_2 parents and their smallest seeded members were quite the equal of the smallest seeded Tom Thumb pop plants. The rather pronounced variation shown by these F_3 families makes it seem possible that a stable type with seeds even smaller than those of Tom Thumb pop might be established by further selection.

TABLE 23. *Frequency distribution of breadth of 25 seeds in cross between California pop and Missouri dent*

Designation	Year	Gen	Class centers in millimeters for breadth of 25 seeds																																		Mean	Coef. var.
			73	78	83	88	93	98	103	108	113	118	123	128	133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208	213	218	223	228	233	238		
499, 500	1910	P_1		4	4	8	3	2																													86.81 ± .90	6.87 ± .72
353	1910	P_2																										1	2	2	2	3	1	1		1	214.54 ± 1.99	4.95 ± .65
502	1910	F_1													1	5	9	2	6	7	1	4	1														151.06 ± 1.17	6.90 ± .55
505	1910	F_2											1		3	5	9	12	6	5	1	3	1														148.33 ± 1.07	6.83 ± .48
834	1911	P_1	1	6	11	7	8	3																													86.59 ± .68	7.26 ± .55
835	1911	P_1		8	10	5	2	1																													83.77 ± .70	6.31 ± .59
833	1911	P_2																										3	1	1	3	5	5	2	2		216.86 ± 1.49	4.76 ± .48
837	1911	F_1															1	3	3	3	6	8	3	1	1												162.83 ± 1.18	5.79 ± .51
836	1911	F_1															2	2	5	7	6	6	2	2													160.66 ± 1.06	5.56 ± .50
829	1911	F_2												2	2	7	5	14	6	4	8	4	3	4	1	2	1										155.30 ± 1.29	9.80 ± .59
830	1911	F_2								1		1	1	3	2	2	6	6	6	7	6	3	1														150.07 ± 1.61	10.75 ± .76
831	1911	F_2									1	1	2	4	1	6	1	9	6	6		1	4		1												148.31 ± 1.51	10.54 ± .73
832	1911	F_2										2	2			1	5	3	11	2	4	12	2	3	1	2	1										157.26 ± 1.56	10.78 ± .70
839	1911	F_3											2	3	2	1	1	6	4	6	9	3	5	4	1	1											157.17 ± 1.57	10.25 ± .71
840	1911	F_3										2	1	10	5	11	11	5	6	2		1															139.67 ± .86	7.09 ± .46

TABLE 24.—*Frequency distribution of breadth of 25 seeds in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Parent class	Class centers in millimeters for breadth of 25 seeds																										No.	Mean	Coef. var.
				113	118	123	128	133	138	143	148	153	158	163	168	173	178	183	188	193	198	203	208	213	218	223	228	233	238			
353...	1910	P	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	1	2	2	2	3	1	1	......	1	13	214.54 ± 1.99	4.95 ± .65
508...	1910	P	......	......	1	2	3	3	4	4	1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	18	134.39 ± 1.29	6.05 ± .68
509...	1910	F1	......	......	......	......	......	......	......	......	......	1	1	2	3	2	4	3	6	1	1	......	1	......	......	......	......	......	......	25	175.00 ± 1.79	7.56 ± .72
510...	1910	F2	......	......	......	......	......	......	5	7	12	10	31	23	24	15	26	12	12	6	5	......	......	......	......	......	......	......	......	188	167.55 ± .70	8.51 ± .50
128...	1911	F2	178	......	......	......	1	1	......	6	3	10	5	11	3	7	7	1	3	1	......	......	......	......	......	......	......	......	......	59	162.23 ± 1.24	8.70 ± .54
127...	1911	F2	198	......	......	......	......	......	......	......	......	1	4	5	7	12	11	7	5	5	1	4	......	1	......	1	......	......	......	64	178.78 ± 1.17	7.74 ± .46
139...	1911	F3	143	1	6	1	6	10	13	15	9	8	6	4	1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	80	141 31 ± .93	8.70 ± .46
140...	1911	F3	148	1	1	......	5	13	12	13	12	10	5	2	1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	75	142.73 ± .81	7.28 ± .39
135...	1911	F3	158	......	......	1	3	2	4	7	7	7	10	12	6	2	4	......	......	1	......	......	......	......	......	......	......	......	......	66	154.97 ± 1.16	8.98 ± .53
132...	1911	F3	158	......	......	......	......	......	2	2	7	4	2	7	1	1	1	......	......	......	......	......	......	......	......	......	......	......	......	27	155.03 ± 1.30	6.46 ± .59
134...	1911	F3	168	......	......	......	......	......	......	2	2	2	6	5	9	6	7	3	......	1	......	......	......	......	......	......	......	......	......	43	167.20 ± 1.15	6.67 ± .49
142...	1911	F3	173	......	......	......	......	......	......	1	......	4	4	5	4	9	7	6	1	2	......	......	......	......	......	......	......	......	......	43	170.91 ± 1.17	6.68 ± .49
143...	1911	F3	178	......	......	......	......	......	......	......	1	1	5	7	5	9	10	13	2	......	......	......	......	......	......	......	......	......	......	53	172.90 ± .90	5.60 ± .37

INHERITANCE OF HEIGHT OF PLANTS.

Tables 25, 26, and 27 contain the data on the heights of the plants in the three crosses 60-3x54, 60-5x54, and 60-8x54,—Tom Thumb pop crossed with Black Mexican sweet. As stated before, these crosses differ only in the fact that separate individuals were the parents. In a cross-fertilized species like maize, however, this might give as varied results as crosses between different commercial varieties. The crosses having been made originally for the purpose of studying other characters, the height frequencies of No. 60 and of the F_1 generation were not recorded. It is only known that the extreme individuals of No. 60 were 22 and 40 inches and that the extreme individuals of the F_1 generation of cross 60-3x54 were 55 and 88 inches. But one is comparatively safe in supposing that both populations exhibited variation approaching that of a normal curve. Granting this assumption, the modal classes of No. 60 and No. 54 were 31 inches and 73 inches, respectively. There was a difference, then, of 42 inches between the classes of greatest frequency of the two parents, and a difference of 18 inches between the plus extreme of the shorter parent and the minus extreme of the taller parent. If the F_1 generation was exactly intermediate between the two parents, its modal class would be about 52 inches. In reality, however, it is about 70 inches. In other words, it has been pushed up about six classes above the intermediate position. This phenomenon is not to be regarded as an expression of dominance. It is due to the increased vigor (largely internodal) that appears when many gametic factors are in the heterozygous condition (East, 1909).

Since no coefficient of variability of the F_1 generation can be calculated, it is useless to calculate it for the F_2 and F_3 generations. There are a number of facts germane to our thesis to be discovered by a simple inspection of Table 25. Three F_2 families were grown and in every case the extremes of these distributions overlap those of the parental distributions. If segregation has occurred, F_3 families from F_2 parents of different height should show different average heights and different amounts of variability. Such results were obtained. The progeny of several short F_2 individuals were, in general, short, and the distributions were different in their variability. The mode of the daughters of (60-3x54)-5-3 was 37 inches, while the mode of the daughters of (60-3x54)-1-7 was 58 inches. The parental types were not recovered in the F_3 generation, but there is good reason—from the appearance of the F_3 distributions—to believe this could be done by further selection.

The F_2 distribution in cross 60-5x54 (Table 26) was much more variable than the F_1 distribution. Only one family from this cross was followed to the F_3 generation, however, so no comparison between progenies of large and of small plants can be made.

Passing to cross 60-8x54 (Table 27) one finds the same increased variability in F_2 over that shown by the F_1 generation. There two plants were followed to the F_3 generation. One was a comparatively short plant 43 inches high; the other was a tall plant 85 inches high. The range of the first fraternity was from 28 inches to 55 inches with the mode about 40 inches. It is clearly a larger type than the original Tom Thumb. Part of this height may be due to the vigor of heterozygosis, but certainly the maternal parent is not reproduced. The other distribution, that from the tall stalk, is remarkable for its extreme variability. Its members range from 37 inches to 91 inches with the mode at about 61 inches. The modes of the two families differ therefore by something like 21 inches. One can scarcely doubt the possibility of recovering a very tall strain from this highly variable family, by continued selection.

Table 28 shows the results from a cross between a small flint, No. 5, and a large dent, No. 6. The mean of the first variety is 68 inches and the mean of the second variety 101 inches. The coefficient of variability of the F_1 generation is about the same as that of the flint parent. The coefficients of variability of the four F_2 families are significantly greater. One has only to examine the range of variation to see this. Individuals were obtained with the complete range from the smallest individuals of the small variety to the largest individuals of the large variety. The coefficient of variability of F_1 is $8.68 \pm .55$, while those of the F_2 families are $15.75 \pm .68$, $13.34 \pm .68$, $12.02 \pm .58$, and $12.65 \pm .46$, respectively.

No F_3 families can be reported for this cross, because the location of the experiment was of necessity moved northward and the plants would not mature.

Table 29 contains the data secured from a cross of Tom Thumb pop and Missouri dent, very short and rather tall strains respectively. The cross was made in the greenhouse in the winter of 1908-9 and the F_1 generation grown the following summer as No. 170. The two parent plants grown in the greenhouse were from open pollinated ears and no selfed seed was obtained from either plant. There was grown, however, along with the F_1 plants in 1909, representatives of the two parents—146, Missouri dent, and 151, Tom Thumb pop—from the same open-pollinated ears from which the two greenhouse plants used in the cross were grown. The plants of all three of these families were measured, but the data were recorded in six-inch classes and therefore can not be presented in a table in which one-decimeter classes are used. The extreme fluctuations of the families are, however, shown in the table by means of arrows. F_1 is plainly intermediate between the parents but somewhat nearer the large than the small parent.

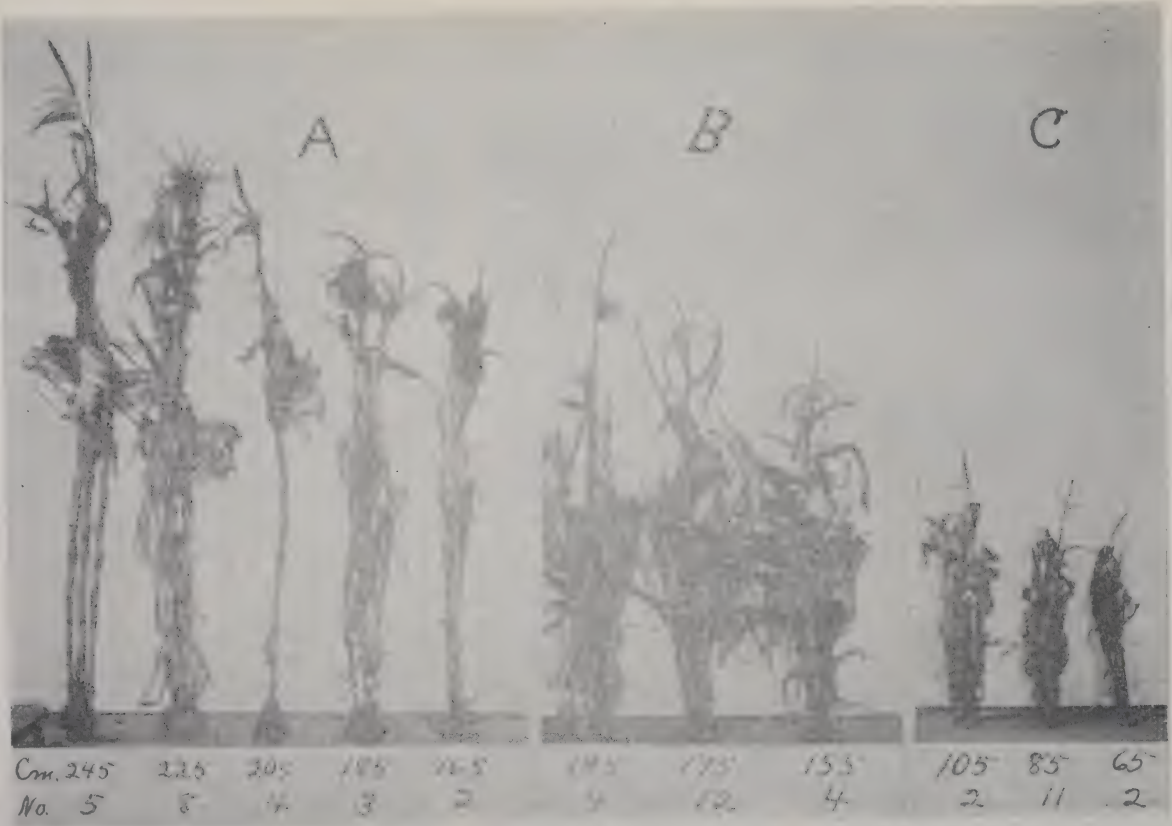
A
B
C
Cm. 245 225 205 185 165 195 175 155 105 85 65
No. 5 5 4 3 2 9 12 4 2 11 2

Fig. 12. Height of plants in 1910. *A*, Missouri dent; *C*, Tom Thumb pop; and *B*, F_1 generation of cross between these varieties.

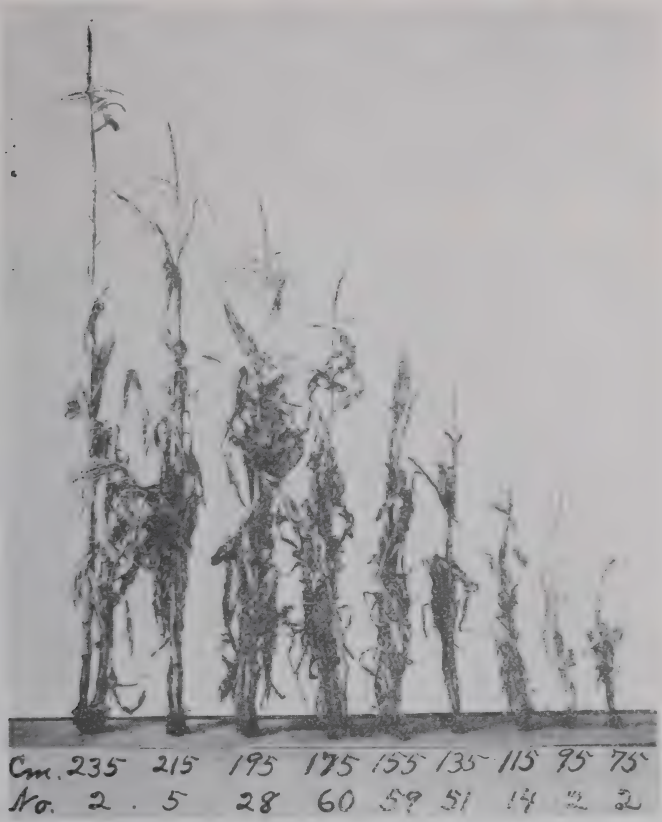
Cm. 235 215 195 175 155 135 115 95 75
No. 2 5 28 60 59 51 14 2 2

Fig. 13. Height of plants of the F_2 generation of Tom Thumb × Missouri dent, as grown in 1910.

In 1910 the parent varieties and a small number of F_1 plants were again grown for comparison with the F_2 generation. No. 509, the F_1 generation, is from the same crossed ear that produced No. 170, No. 508 from the same ear as No. 151, and No. 363 from the same ear as No. 146. Again the F_1 generation was intermediate between the parents in height of stalks with a comparatively small range of variation. The F_2 generation, family 510, contained some plants quite as small as the smallest of Tom Thumb pop and some as large as the average of the Missouri dent, with all gradations between. Since no selfed seed was obtained from the two original plants used in the cross it cannot be known in how far they were heterozygous for size genes. That the seeds of the original ear of Missouri dent had different size potentialities is indicated by the difference between the four fraternities, 353, 354, 357, and 358, which were grown from selfed seed of different individual plants of No. 146.

In 1911 the parent stocks, two F_2 families, and several F_3 lots were grown side by side. The F_2's again showed greater variation than the parents as indicated both by the range of heights and by the coefficients of variation, tho no individuals were quite so small as those of the small parent and few so large as those of the large parent. None of the F_3 progenies exhibited the range of variation shown by the F_2 fraternities, tho as measured by the coefficient of variation some of them were practically as variable. Measured by the same standard, however, some of them were even less variable than the parent stocks, but whether any of them were homozygous in all or most of their size factors can only be told by growing another generation. No F_3 family was so small as Tom Thumb pop and

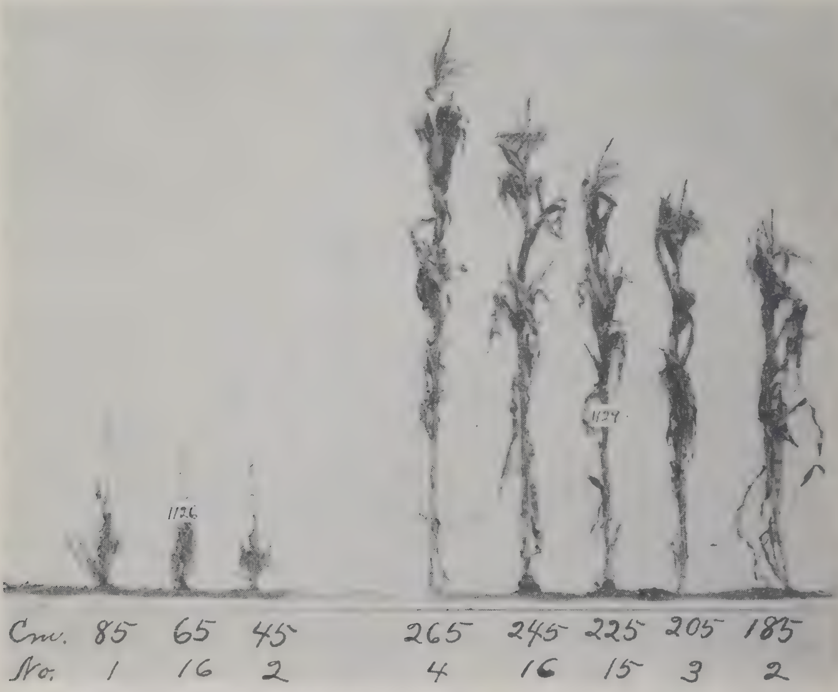

Fig. 14. Height of plants in 1911—Tom Thumb pop at the left and Missouri dent at the right.

none such was to have been expected, since none of them came from the smallest F_2 plants. One of the F_3 families, 1149, from the tallest F_2 plant of the previous year, however, exceeded the Missouri dent parent stock in height. This fact is probably not to be ascribed to any new combination of height factors not found in the tall parent variety but rather to the fact that the vigor of the Missouri dent families grown in 1911 had been reduced by previous selfing. Nos. 1129, 1130, and 1148, the latter two duplicates, were from selfed ears of No. 353, which was grown from a selfed ear of No. 146.

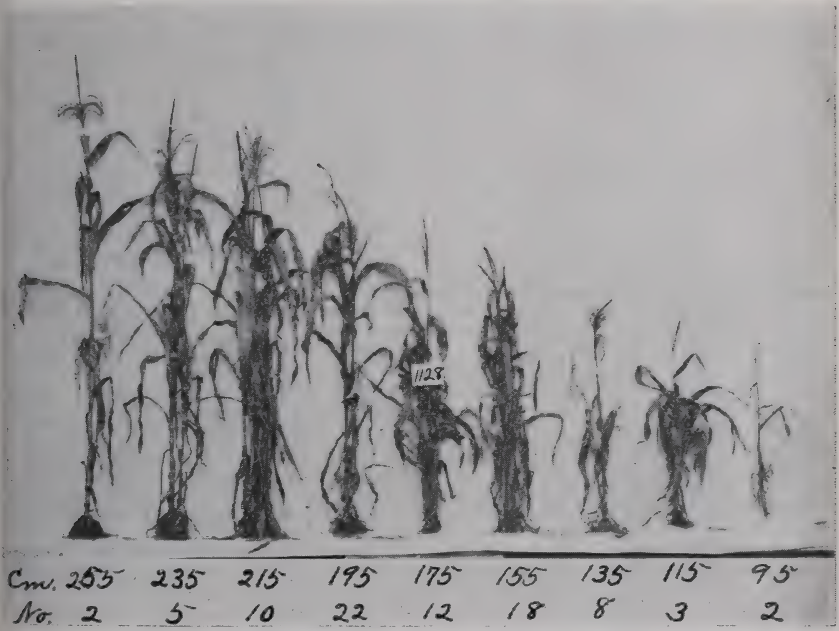
1128
Cm. 255 235 215 195 175 155 135 115 95
No. 2 5 10 22 12 18 8 3 2

Fig. 15. Height of plants of the F_2 generation of Tom Thumb pop × Missouri dent, as grown in 1911.

The variation in height within any lot of the parent varieties and within the F_1 generation would necessarily be influenced by heterozygosity in the size factors of the parent stocks, the variation increasing with an increasing number of heterozygous size genes. The same condition might also result in noticeable differences between F_2 families grown from different F_1 ears as well as between different selfed strains of the parent varieties. *Nothing of the sort, however, can explain the great variation within any one F_2 progeny, nor the pronounced differences between the several F_3 fraternities arising from a single F_2 family.*

All the F_3 families from which data are at hand came from a single F_2 fraternity, No. 510, which, of course, came from a single F_1 plant, and this plant from the union of a single gamete from each of the parents. Whether all the other gametes produced by those two parent plants were like the two concerned in this cross or whether they were of several different sorts can obviously have no bearing on the behavior of the one F_1 plant, the single F_2 family, and the several F_3 families in question, because these other sorts of gametes, if there were such, had no connection with this line of progenies. In other words, the possible, or even probable, fact that the parent plants may not have been homozygous in all size factors can in no way lessen the importance of the principal conclusions to be drawn from this and similar tables. *There is no escape from the fact that segregation in F_2 occurs with respect to size factors just as truly as it does with factors for other characters. There is also no getting around the plain indications derived from the F_3 progenies that F_2 size segregates may serve as the basis of permanent, true-breeding types just as in case of various other Mendelizing characters.*

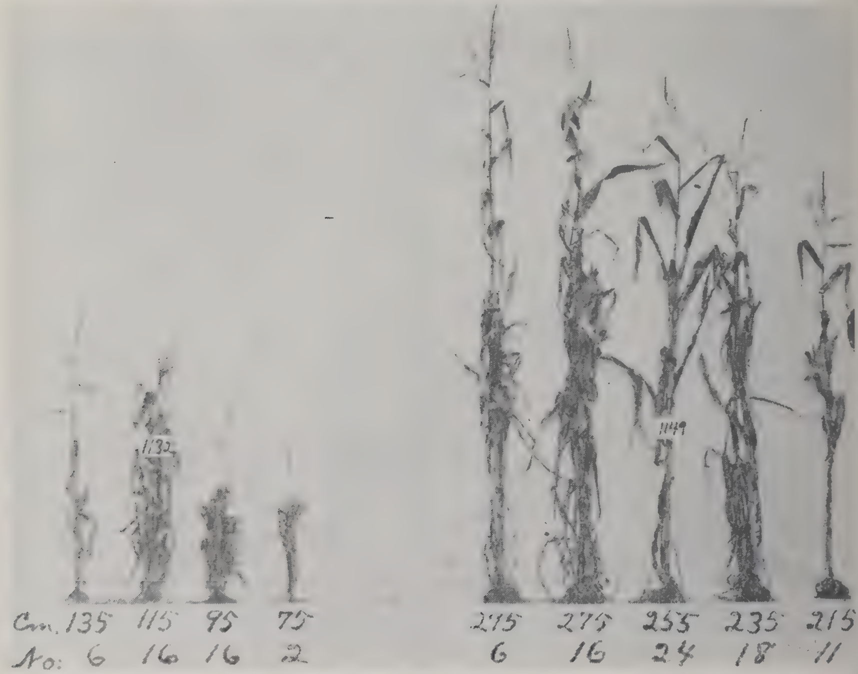
1132
1149
Cm. 135 115 95 75 275 275 255 235 215
No: 6 16 16 2 6 16 24 18 11

Fig. 16. Height of plants of the shortest and tallest F_3 families of Tom Thumb pop × Missouri dent as grown in 1911.

It will not lessen the value of the indications noted above to call attention to the fact that the inherent differences between the F_3 fraternities were exaggerated somewhat by a peculiar combination of weather conditions with characters of the plants other than size. It happens that Tom Thumb pop is not only small but also extremely early and that Missouri dent is very late as well as large. Now as will be shown later (see Table 39), earliness segregates as does size. Whether thru genetic correlation or not, it happened that the short F_3 families were also early and the tall families late. The weather of early summer when the early families were developing rapidly was very unfavorable for growth while the weather late in summer when the late families were making their most rapid growth was very favorable. The early families were, therefore, shorter and the late families taller than they would have been had the conditions been more uniform thruout the season. This effect of the weather is readily seen by noting the various F_3 fraternities and the sizes of the F_2 plants from which they were grown. In case of each F_3 family the size class to which the F_2 parent plant belonged is indicated by blackfaced figures in the F_3 array. The

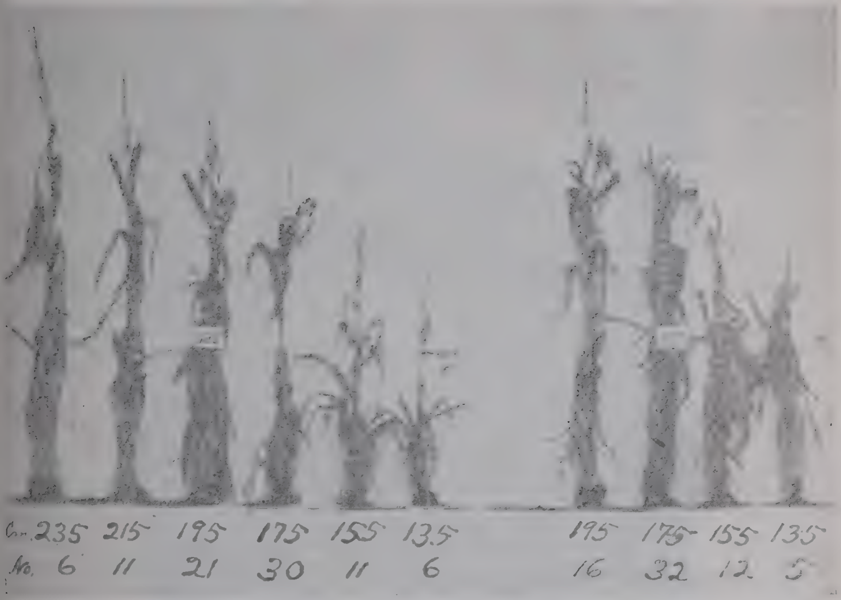

Fig. 17. Height of plants of two F_3 families of Tom Thumb × Missouri dent, as grown in 1911.—Note difference in variability.

short F_3 families are in general shorter and the tall families taller than the F_2 plants from which they were derived. Moreover, the range of variation of the F_2 plants grown in 1911 was probably increased by the weather conditions, the early plants

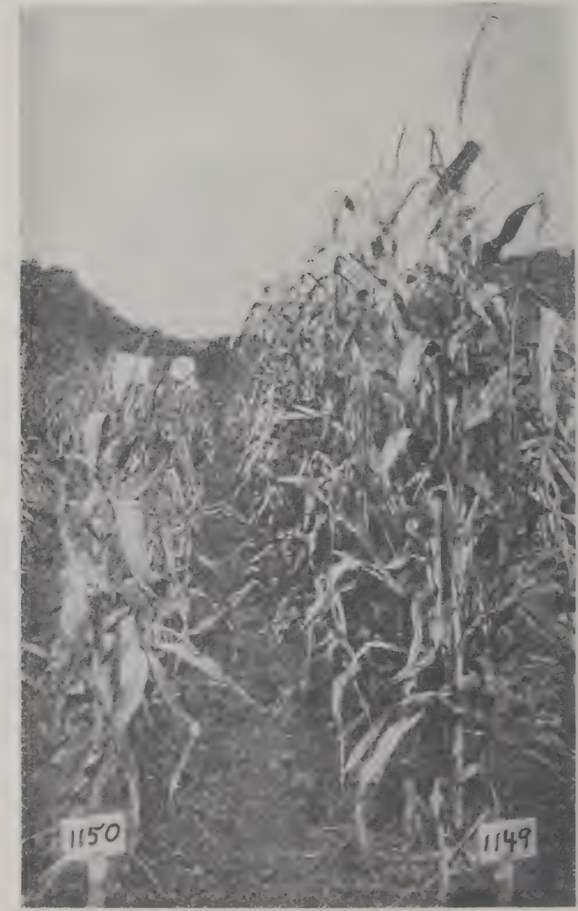

Fig. 18. The tallest and one of the shortest F_3 families of Tom Thumb × Missouri dent as they appeared in the field September 19, 1911.

doubtless having been made shorter and the late plants taller than they would otherwise have been. But it must also be remembered that the same influences must necessarily have been felt by the early and late parent stocks, thereby making the gap between them greater than it would otherwise have been. It is true that a comparison of heights of the Missouri dent families grown in 1911 with the heights of the 1910 plants from which they came does not show the same effect noticed in case of the late F_3 families, but this is most likely due to the repeated selfing of the parent stocks.

Early in the study of this cross it was foreseen that the great difference in earliness between the parents might introduce the complication discussed above, and an endeavor was therefore made to overcome the difficulty in later crosses by using as parents varieties that, while differing much in size, had practically the same season of growth. The varieties chosen were Missouri dent, the same one used as tall parent in the cross already described, and California Rice pop. The latter is only a little taller than Tom Thumb pop and, while it ripens somewhat earlier than Missouri dent, its time of blossoming and consequently its duration of growth are not appreciably different from Missouri dent. California pop also differs much from Tom Thumb in the number of nodes per stalk. In this respect it is very similar to Missouri dent. The difference in height between Tom Thumb pop and Missouri dent is largely a difference in number of internodes, while the difference between California pop and Missouri dent is largely one of internode length. (See Tables 31 to 34.) The one cross, therefore, supplements the other well in this study of the inheritance of height of stalks, since height is apparently merely a product of number of nodes and internode length.

In Table 30 are brought together the available data derived from the cross between Missouri dent and California pop. As in the preceding table, the progenies grown in the same garden the same year are grouped together. Of the lots grown in 1910, No. 353 is from selfed seed of a single plant of Missouri dent, 499 and 500 are from selfed seed of two plants of California pop, and Nos. 502 and 505 are from crosses of the parent plants of 499 and 500 with the parent plant of 353. In this case, therefore, the F_1 generation is fully comparable with the parent generations grown the same year. In 1911, two families, 833 and 838, were grown to represent Missouri dent. They were from selfed seed of two plants of 353. Likewise two lots, 834 and 835, grown from selfed seed of two plants of 499, represent California pop. Nos. 836 and 837 consisted of F_1 plants from the remnants of the same ears from which had been grown the previous year Nos. 505 and 502 respectively. Nos. 829, 830, 831, 832, 839, and 840 were F_2 progenies from selfed seed of six different F_1 plants.

The F_1 lots of both years were almost as tall as the tall parent, which is in marked contrast to the intermediate F_1 plants of the cross of Tom Thumb pop and Missouri dent. The difference in behavior is undoubtedly due to the fact that in the one cross number of nodes was the important consideration while in the other it was internode length and to the further fact that F_1 plants in general have an intermediate number of internodes but an internode length greater than that of the tall parent. (See Tables 31 to 34.) That the tallness of the F_1 plants of the cross under consideration was not due to dominance of long over short internodes but rather to the increased vigor accompanying heterozygosis of many characters is indicated by the fact that the mean height of the F_2 fraternities was practically the mid-parental height—partial homozygosis having occurred in F_2—and also by the fact that the F_2 frequency distributions were not so pronouncedly skewed as they would have been if great internode length were dominant. The difference between the several F_2 families is probably due to the presence of heterozygous size factors in one or more of the parent plants. No one F_2 fraternity covers the entire range between the outer extremes of the two parents and no F_2 fraternity fails to bridge the gap between the inner extremes of the parents. The larger variation coefficients of the F_2 families indicate segregation of size factors in this cross where internode length was principally concerned just the same as in the other cross where number of nodes was the main difference and with this cross, moreover, there can be no question of the influence of favorable weather at one time and unfavorable weather at another.

TABLE 25.—*Frequency distribution of heights of plants in cross (60-3x54).*

Designation	Gen.	Parent class	Class centers in inches for heights of plants																									
			22	25	28	31	34	37	40	43	46	49	52	55	58	61	64	67	70	73	76	79	82	85	88	91	94	97
54	P	......	......	......	......	......	......	......	......	......	......	......	......	......	2	6	10	17	24	26	21	14	14	7	3	1		
60	P	......	<—	—	—	—	—	—	—>																			
(60-3x54)	F1	......	......	......	......	......	......	......	......	......	......	......	......	—	—	—	—	—	—	—	—	—	—	—	—>			
(60-3x54)-1	F2	......	......	......	......	......	......	1	5	2	2	9	24	12	29	10	14	7	4	1								
(60-3x54)-5	F2	......	......	......	......	......	......	2	5	7	24	19	33	30	26	13	19	4	3	2								
(60-3x54)-6	F2	......	......	......	......	......	......	2	5	4	6	3	11	18	17	11	14	3	6	2								
(60-3x54)-total	F2	......	......	......	......	......	......	5	15	13	32	31	68	60	72	34	47	14	13	5								
(60-3x54)-1-1	F3	37	....	1	5	10	20	30	31	34	26	20	12	5														
(60-3x54)-1-3	F3	40	......	......	......	3	13	10	21	14	12	10	2															
(60-3x54)-1-7	F3	61	......	......	......	......	......	......	......	......	3	18	14	40	53	47	43	21	10	3	1	1						
(60-3x54)-5-2	F3	43	......	......	......	5	3	2	5	10	14	4	2															
(60-3x54)-5-3	F3	40	......	4	11	25	25	36	23	33	16	9	1	2														
(60-3x54)-6-5	F3	40	......	......	2	2	4	9	18	14	22	23	5	5	2													

TABLE 26.—*Frequency distribution of heights of plants in cross (60-5x54).*

Designation	Gen.	Parent class	Class centers in inches for heights of plants																									
			22	25	28	31	34	37	40	43	46	49	52	55	58	61	64	67	70	73	76	79	82	85	88	91	94	97
54	P	......	......	......	......	......	......	......	......	......	......	......	......	......	2	6	10	17	24	26	21	14	14	7	3	1		
60	P	......	<—	—	—	—	—	—	—>																			
(60-5x54)	F1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	<—	—	—	—	—	—	—	—	—>				
(60-5x54)-2	F2	......	......	......	......	......	......	1	......	......	1	4	......	3	15	31	37	18	10	12	9	1						
(60-5x54)-6	F2	......	....	......	......	......	......	......	......	1	2	6	10	16	21	27	23	19	10	3	......	......	1					
(60-5x54)-8	F2	......	......	......	......	......	......	......	......	......	2	2	9	8	22	19	24	12	4	3	3							
(60-5x54)-11	F2	......	......	......	......	......	......	......	2	......	2	3	3	12	20	28	24	17	7	4								
(60-5x54)-12	F2	......	......	......	......	......	......	1	......	......	1	3	4	5	17	12	18	26	28	9	10	2	2					
(60-5x54)-total	F2	......	......	......	......	......	......	2	2	1	8	18	26	44	95	117	126	92	59	31	22	3	3					
(60-5x54)-11-2	F3	43	......	......	......	......	......	5	9	14	32	22	20	17	3	1												

TABLE 27.—*Frequency distribution of heights of plants in cross (60-8x54).*

Designation	Gen.	Parent class	22	25	28	31	34	37	40	43	46	49	52	55	58	61	64	67	70	73	76	79	82	85	88	91	94	97
			Class centers in inches for heights of plants																									
54	P	......	......	......	......	......	......	......	......	......	......	......	......	......	2	6	10	17	24	26	21	14	14	7	3	1		
60	P	......	<—	—	—	—	—	—	—>																			
(60-8x54)	F1	......	......	......	......	......		......	......	......	......	......	<—	—	—	—	—	—	—	—	—	—	—	—>				
(60-8x54)-1	F2	......	......	......	......	......	......	1	......	......	4	5	8	9	23	17	21	11	13	9	5	2	1	......	1			
(60-8x54)-8	F2	......	......	......	......	......	......	......	......	1	1	1	5	4	12	12	15	16	8	11	4	4	3	1				
(60-8x54)-total	F2	......	..	......	......	......	......	1	......	1	5	6	13	13	35	29	36	27	21	20	9	6	4	1	1			
(60-8x54)-1-1	F3	43	......	......	5	6	10	17	16	16	7	10	6	3														
(60-8x54)-8-8	F3	85	......	......	......	......	......	4	4	5	3	8	10	11	14	20	16	15	17	11	8	6	4	......	......	1	.	

TABLE 28.*—*Frequency distribution of heights of plants in cross (5x6).*

No.	51	54	57	60	63	66	69	72	75	78	81	84	87	90	93	96	99	102	105	108	111	Mean	Coef var
	Class centers in inches for heights of plants																						
5	3	2	4	5	11	17	17	18	10	6	4	......	......	......	......	......	......	......	......	......	......	68.22 .41	9.51 .42
6	......	......	......	......	......	......	......	......	......	......	......	......	1	2	2	13	14	16	14	8	3	101.18 .40	5.01 .28
(5x6) F1	......	......	......	......	......	......	......	......	......	......	5	4	3	9	9	6	5	4	4	7	......	94.53 .74	8.68 .55
(5x6)-1 F2	2	1	3	6	3	5	10	10	22	16	10	7	11	13	6	10	8	4	4	2	......	81.00 .69	15.75 .68
(5x6)-2 F2	......	......	......	2	......	2	4	2	6	5	12	8	12	6	5	8	3	10	8	2	2	88.33 .80	13.34 .68
(5x6)-8 F2	2	......	......	......	4	4	12	7	9	13	12	15	10	8	8	1	1	1	......	......	......	79.46 .62	12.02 .56
(5x6)-14 F2	......	1	2	4	2	7	8	17	21	11	27	24	16	9	11	10	5	4	2	......	......	81.24 .51	12.65 .45

* Grown side by side in same season.

TABLE 29.—*Frequency distribution of heights of plants in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Class centers in decimeters for height of plants																										Mean	Coef. var.
			5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
146	1909	P																	<—	—	—	—	—	—	—>					
151	1909	P				<—	—	—	—>																					
170	1909	F_1										<—	—	—	—	—	—	—	—>											
363	1910	P																	2	4	9	9	6	11	11	2	1		24.93 ± .17	7.68 ± .49
353	1910	P												1	1	2	1	3	1	6	2	4	1						21.27 ± .35	11.44 ± 1.18
357	1910	P													2	1	2	6	2	4	3	3							20.91 ± .29	9.87 ± .98
354	1910	P														1		4	2		2	3	3	2	2	1	2		23.86 ± .45	13.08 ± 1.35
358	1910	P															2	1	1	5	4	1	3	3	1	1			23.32 ± .35	10.37 ± 1.07
508	1910	P			2	6	5	2																					8.47 ± .15	10.44 ± 1.30
509	1910	F_1											1	3	5	7	4												17.50 ± .17	6.39 ± .68
510	1910	F_2			2			2	8	6	25	26	29	30	32	28	22	6	4	1	2								15.86 ± .12	16.65 ± .53
1130	1911	P															2		5	3	4	2	**3**†	1					22.50 ± .29	8.49 ± .91
* 1148	1911	P													1	1	..		2	2	4	4	**4**	1	1				23.10 ± .36	10.42 ± 1.12
1129	1911	P															2	1	2	4	**11**	10	6	3	1				23.40 ± .19	7.51 ± .57
1126	1911	P	2	9	7	1	**0**																						6.37 ± .12	11.66 ± 1.29
1127	1911	F_2					1	1	2	3	5	4	1	**6**	11	3	6	13	11	4	3	3							17.97 ± .28	19.93 ± 1.13
1128	1911	F_2					1	1	..	3	3	5	11	7	4	**8**	12	10	5	5	2	3	1	1					17.87 ± .26	19.40 ± 1.09
1132	1911	F_3				2	5	11	11	**5**	5	1																	10.78 ± .15	13.20 ± 1.01
1134	1911	F_3				1	3	10	6	13	**9**	7	5	5	4	1													12.70 ± .20	18.55 ± 1.14
* 1150	1911	F_3				1	3	4	7	8	**5**	6	5	5	4	2													13.12 ± .25	19.55 ± 1.37
1133	1911	F_3				1	4	3	15	21	9	**7**	3	1															11.98 ± .13	12.65 ± .77
1137	1911	F_3									3	2	**3**	9	20	12	13	3											17.22 ± .14	9.53 ± .67
1139	1911	F_3											**4**	2	3	13	12	20	10	16	7	2	1						20.01 ± .15	10.75 ± .55
1135	1911	F_3									2	4	7	**4**	13	17	16	5	9	2	3	3							18.31 ± .18	13.64 ± .72
1145	1911	F_3										5	2	6	**2**	12	12	12	14	8	4	3	2						19.49 ± .20	13.44 ± .72
1140	1911	F_3											1	3	**6**	6	5	5	15	17	16	6	3	2					21.13 ± .18	11.68 ± .61
1142	1911	F_3												6	**3**	17	10	22	9	11	3	1							19.60 ± .14	9.49 ± .51
1138	1911	F_3													3	**4**	2	12	12	16	15	15	9	3	4	1			22.39 ± .16	10.62 ± .52
1141	1911	F_3										1	3	5	7	6	**11**	17	17	13	3	4							19.80 ± .16	11.43 ± .59
1131	1911	F_3													2	3	**6**	16	22	12	5	5							20.89 ± .13	7.52 ± .43
* 1147	1911	F_3															**2**	5	13	19	16	16	6	1					22.53 ± .12	6.73 ± .37
1143	1911	F_3														8	**6**	9	5	16	17	11	9	5	1				22.21 ± .17	10.42 ± .53
1146	1911	F_3														1	**4**	6	16	19	17	12	7	4	5	1	1		22.77 ± .15	9.53 ± .47
1144	1911	F_3															**1**	1	3	16	14	21	18	6	6	1			23.86 ± .12	7.20 ± .37
1149	1911	F_3																	5	6	**12**	6	12	12	10	6	6	1	25.14 ± .18	9.28 ± .51

* Duplicates.

† Black type indicates the class to which the parent belonged.

TABLE 30.—*Frequency distribution of height of plants in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Class centers in decimeters for height of plants																				Mean	Coef. var.
			6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		
353	1910	P											1	1	2	1	3	1	6	2	1	1	21.27 ± .35	11.44 ± 1.18
199 and 500	1910	P				1	2	7	8	1													11.32 ± .14	8.12 ± .89
502	1910	F1											1	2	1	5	13	5	1				19.64 ± .17	6.70 ± .60
505	1910	F1												1	1	4	6	8	1	1			20.18 ± .19	6.45 ± .66
833	1911	P									1	5	11	16	22	13	11	4	1	0	1		18.00 ± .13	9.83 ± .51
838	1911	P									1	1		4	5	5	2	1					18.05 ± .25	9.07 ± .99
834	1911	P			1	9	18	16	7														10.37 ± .09	9.56 ± .64
835	1911	P	1	2	11	21	14	2															9.00 ± .09	10.69 ± .70
836	1911	F1							1	0	1	2	2	6	11	12	3						17.80 ± .17	9.05 ± .67
837	1911	F1										2	6	9	9	3	1						17.27 ± .15	6.83 ± .60
829	1911	F2					1	1	4	10	13	14	13	20	8	8	2	1					15.75 ± .15	13.90 ± .69
830	1911	F2		1		2	3	9	12	12	19	22	10	3	2								13.65 ± .14	14.98 ± .75
831	1911	F2			2	0	5	6	13	14	29	14	7	6									13.54 ± .13	14.05 ± .70
832	1911	F2					2	5	11	17	12	12	15	9	7	5	1						14.69 ± .16	15.83 ± .79
839	1911	F2				1	1	2	7	8	13	17	11	9	2								14.58 ± .15	12.76 ± .72
840	1911	F2			1	1	0	2	2	7	9	17	19	6	7	3							15.19 ± .16	13.77 ± .78

THE INHERITANCE OF NUMBER OF NODES PER STALK.

In case of the crosses of Missouri dent with Tom Thumb pop and of Missouri dent with California pop, discussed under the head of the inheritance of height of plant, the nodes of the main stalk of each plant were counted at the time the stalks were measured. The results of these counts are presented in Tables 31 and 32. Since the relationship of the various families was given in some detail in the discussion of height, it will not be necessary to repeat it here.

In case of Missouri dent crossed by Tom Thumb, where the number of nodes is very unlike in the parent varieties, the F_1 numbers were distinctly intermediate between the parents and scarcely bridged the gap between them. The three F_2 families showed much greater variation than the parents and the F_1 generation. They overlapped both parents but did not contain individuals with so many nodes as the largest number found in the tall parent nor individuals with so few nodes as the least number observed in the short parent. The total range of variation exhibited by the F_3 fraternities was greater by three nodes than that of the F_2 fraternities, but possibly would not have been so had an equal number of F_2 plants been grown. In no single F_3 family was the variation so great as in the F_2 lots and in some families it was no greater than in case of the parents. While the parent types were not completely recovered in the F_3 lots, the difference between the several F_3's was notable. For instance the largest number of nodes recorded in families 1132 and 1133 (Table 31) was thirteen, while the smallest number noted in families 1144, 1147, and 1149 was fifteen.

California pop, tho very short, is unlike Tom Thumb pop in that it has nearly as many nodes as Missouri dent. In the cross of these two varieties (Table 32), F_1 was intermediate between the parents. With the parents so nearly alike, it would seem that individuals like the extremes of both parents should have appeared in F_2 even with smaller numbers than were grown. Four F_2 families contained plants with as many nodes as the greatest number shown by any Missouri dent plant, but no F_2 family contained a plant with so few nodes as some of the plants of California pop. In this connection it should be noted that California pop produces numerous tillers while Missouri dent produces very few. It seems possible that the small number of nodes in California pop may in some way be associated with the large number of tillers.

TABLE 31.—*Frequency distribution of number of nodes per stalk in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Parent class	Classes for number of nodes per stalk																				Mean	Coef. var.
				5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
146.	1909	P	......	......	......	......	......	......	......	......	......	......	......	......	......	7	10	1	3	1	......	......	......	18.14 ± .16	6.28 ± .64
151.	1909	P	......	......	......	......	1	4	1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	9.00 ± .16	6.41 ± 1.25
170.	1909	F1	......	......	......	......	......	......	1	3	4	6	3	......	1	......	......	......	......	......	......	......	......	12.61 ± .21	10.94 ± 1.32
363.	1910	P	......	......	......	......	......	......	......	......	......	......	......	......	......	2	6	10	15	13	8	2	......	20.13 ± .13	7.10 ± .45
353.	1910	P	......	......	......	......	......	......	......	......	......	......	......	......	......	2	6	6	4	1	...	3	......	19.36 ± .25	9.02 ± .92
357.	1910	P	......	......	......	......	......	......	......	......	......	......	......	......	5	2	8	5	2	...	1		......	18.04 ± .21	8.25 ± .82
354.	1910	P	......	......	......	......	......	......	......	......	......	......	......	......	......	......	2	3	8	6	2	1	......	20.27 ± .17	5.98 ± .61
358.	1910	P	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	2	5	7	2	5	1	21.27 ± .20	6.52 ± .66
508.	1910	P	......	......	......	......	6	5	4	......	......	......	......	......	......	......	......	......	......	......	......	......	......	8.87 ± .14	9.10 ± 1.12
509.	1910	F1	......	......	......	......	......	......	......	......	7	8	4	1	......	......	......	......	......	......	......	......	......	12.95 ± .13	6.66 ± .71
510.	1910	F2	......	......	...	......	2	7	14	30	36	45	34	28	18	6	2	1	......	......	......	......	......	13.04 ± .09	15.69 ± .50
* 1130.	1911	P	21	......	......	......	......	......	......	......	......	......	......	......	......	......	......	2	6	5*	6	1	......	20.90 ± .16	5.22 ± .56
1148.	1911	P	21	......	......	......	......	......	......	......	......	......	......	......	......	......	1	2	8	5	3	1	......	20.50 ± .18	5.67 ± .61
1129.	1911	P	18	......	......	......	......	......	......	......	......	......	......	......	......	1	5	7	15	10	2	......	......	19.85 ± .12	5.80 ± .44
1126.	1911	P	9	1	2	8	8	0	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	7.21 ± .13	11.51 ± 1.28
1127.	1911	F2	13	......	......	......	3	4	10	13	11	9	11	9	4	3	......	......	......	......	......	......	......	12.42 ± .17	18.28 ± 1.03
1128.	1911	F2	13	......	......	......	2	3	15	17	16	9	7	5	5	1	1	1	......	......	......	......	......	12.15 ± .17	18.31 ± 1.00
1132.	1911	F3	9	......	......	2	9	10	6	8	4	1	......	......	......	......	......	......	......	......	......	......	......	9.63 ± .16	15.70 ± 1.21
* 1134.	1911	F3	9	......	......	1	8	7	15	18	7	7	1	......	......	......	......	......	......	......	......	......	......	10.48 ± .13	14.99 ± .91
1150.	1911	F3	9	......	......	......	......	2	9	10	13	8	5	1	2	......	......	......	......	......	......	......	......	11.90 ± .16	13.68 ± .94
1133.	1911	F3	10	......	......	2	6	13	25	12	5	1	......	......	......	......	......	......	......	......	......	......	......	9.91 ± .10	12.31 ± .75
1145.	1911	F3	11	......	......	......	......	......	1	2	3	12	20	16	18	5	5	......	......	......	......	......	......	14.72 ± .12	11.35 ± .60
1135.	1911	F3	12	......	......	......	......	1	3	13	14	26	20	6	2	......	......	......	......	......	......	......	......	12.82 ± .10	10.96 ± .57
1142.	1911	F3	12		......	......	......	......	......	4	10	22	26	13	5	2	......	......	......	......	......	......	......	13.70 ± .10	9.58 ± .51
1137.	1911	F3	14	......	......	......	......	......	1	7	13	22	15	6	1	......	......	......	......	......	......	......	......	13.00 ± .10	9.45 ± .56
1138.	1911	F3	14	......	......	......	......	......	......	1	5	10	20	15	20	12	8	3	2	......	......	......	......	15.32 ± .13	12.44 ± .62
1139.	1911	F3	15	......	......	......	......	......	......	......	1	4	9	13	23	20	8	8	3	1	......	......	......	16.33 ± .13	10.96 ± .56
1143.	1911	F3	15	......	......	......	......	......	......	......	......	2	4	10	19	25	17	6	4	......	......	......	......	16.79 ± .11	9.03 ± .46
1146.	1911	F3	15	......	......	......	......	......	......	......	......	......	2	13	21	19	17	13	6	2	......	......	......	17.17 ± .11	9.42 ± .47
* 1131.	1911	F3	15	......	......	......	......	......	......	......	......	......	5	12	31	16	6	1	......	......	......	......	......	16.13 ± .09	6.58 ± .37
1147.	1911	F3	15	......	......	......	......	......	......	......	......	......	......	2	11	29	24	10	2	......	......	......	......	17.45 ± .08	5.99 ± .32
1141.	1911	F3	16	......	......	......	......	......	......	......	1	4	11	12	19	17	17	5	1	......	......	......	......	16.23 ± .12	10.43 ± .54
1140.	1911	F3	16	......	......	......	......	......	......	......	......	2	11	16	23	16	13	4	......	......	......	......	......	16.12 ± .11	9.04 ± .47
1144.	1911	F3	16	......	......	......	......	......	......	......	......	......	......	3	15	35	20	13	1	......	......	......	......	17.32 ± .08	6.15 ± .31
1149.	1911	F3	17	......	......	......	......	......	......	......	......	......	......	4	11	15	16	14	14	2	......	......	......	17.99 ± .12	8.63 ± .47

* Duplicates.

TABLE 32.—*Frequency distribution of number of nodes per stalk in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Classes for number of nodes per stalk												Mean	Coef. var.
			13	14	15	16	17	18	19	20	21	22	23	24		
499 and 500	1910	P	...	2	8	3	5	1	...	...	...	...	...	...	15.74±.17	7.10±.78
502	1910	F_1	...	...	1	5	9	8	5	...	...	...	...	...	17.39±.14	6.20±.56
353	1910	P	...	...	...	...	2	6	6	4	1	...	3	...	19.36±.25	9.02±.92
505	1910	F_1	...	...	...	2	10	7	2	1	...	...	...	...	17.55±.14	5.35±.54
833	1911	P	...	...	...	3	10	11	27	20	8	6	...	...	19.16±.11	7.64±.40
838	1911	P	...	...	...	...	...	...	2	7	5	4	1	...	20.74±.17	5.15±.56
834	1911	P	1	6	16	7	8	4	7	2	...	...	...	...	16.27±.17	11.02±.74
835	1911	P	3	6	17	11	9	6	1	...	...	...	...	...	15.74±.13	9.00±.59
836	1911	F_1	...	...	...	1	12	15	11	1	1	...	...	...	18.05±.10	5.46±.41
837	1911	F_1	...	...	...	4	13	4	8	...	1	...	...	...	17.67±.15	6.75±.59
829	1911	F_2	...	...	2	9	14	16	21	12	15	5	1	...	18.81±.13	9.68±.47
830	1911	F_2	...	...	...	9	19	19	28	10	6	1	2	1	18.52±.11	8.82±.43
831	1911	F_2	...	...	2	12	14	19	20	14	6	8	1	...	18.61±.13	9.91±.48
832	1911	F_2	...	...	...	2	8	21	23	20	12	4	4	2	19.41±.12	8.69±.42
839	1911	F_2	...	...	1	6	18	20	17	6	3	3	...	...	18.23±.12	8.13±.45
840	1911	F_2	...	...	3	14	23	22	9	2	1	...	...	...	17.41±.09	6.88±.38

INHERITANCE OF INTERNODE LENGTH.

From the data given for height of stalks and number of nodes of the crosses of Tom Thumb pop with Missouri dent and of the latter with California pop, the average internode length per plant was determined. Tables 33 and 34 contain these calculated data.

While in 1909 the height and number of nodes were determined for each individual plant, only the frequencies of the various height and node-number classes were recorded. It is impossible, therefore, to show even the range of internode length for the lots grown that year. From the mean heights and the mean number of nodes of these lots, however, an approximation of the mean internode length can be obtained. These approximate means are indicated by crosses in Table 33. The feature of these entries is that the mean internode length of the F_1 generation is much greater than that of even the Missouri dent parent. It is evident that the increased vigor of F_1 plants is manifested almost wholly by increased internode length, since, as was shown in Table 31, number of nodes is distinctly intermediate.

In 1910, very moist conditions in early summer, when Tom Thumb pop was making its rapid growth, and very dry conditions when the later Missouri dent and F_1 plants were growing most rapidly, tended to equalize the internode lengths of the several families. Notwithstanding this the F_1 internode length was considerably in excess of that of Missouri dent. The mean internode length of the F_2 generation was somewhat less than that of F_1—doubtless because of the decreased vigor accompanying partial homozygosis of various characters—but was still in excess of the internode length of Missouri dent. The range of variation in F_2, No. 510, was somewhat remarkable when considered in connection with the ranges of the parents. The greatest internode length in F_2 was thirty millimeters greater and the shortest thirty millimeters less than the respective extremes found among the parents. This increased range may doubtless be accounted for in part, tho certainly not entirely, by the fact that more individuals were included in F_2 than in all the other lots together. It seems scarcely possible that the very weather conditions that tended to increase the internode length of the early Tom Thumb pop and to decrease that of the late Missouri dent, and thereby to restrict the combined range of variation of the parents, could have had the opposite effect on the F_2 range. There was, as a matter of fact, in this particular F_2 family, No. 510, a correlation between earliness and internode length of about .21. In other words, there was some tendency at least for the early plants to have long internodes and the late plants short internodes. This correlation is probably a mere expression of the effect of the seasonal differences in weather, accelerating the growth of the early plants and retarding that of the late ones. If, however, this correlation were genetic, or even merely physiological, so that, without respect to seasonal weather changes, the early plants tended to have longer internodes than the late plants, then the weather actually experienced in 1910 would have tended to make the long internodes longer and the short ones shorter, thus tending to extend the range of variation of F_2 while lessening that of the parents. But it is difficult to see how there can be any physiological correlation between earliness and long internodes. And it is even more difficult to believe in *genetic* correlation between *earliness* and *long internodes* when it is remembered that in case of the parents the *early* one has the *shorter* internodes. On the whole, therefore, it seems very probable that the production of internode lengths in F_2 both above the upper and below the lower extremes of the parents was due in part at least to new combinations of internode-length factors.

If the above is the correct explanation of the very long and the very short internode types that appeared in F_2 family No. 510, it should be possible to isolate strains from it that have longer or shorter internodes than do the parent varieties. The selection of F_2 plants to be tested by F_3 progenies was based upon height of stalk and upon earliness rather than upon internode length, and it happened that no F_2 plant with extremely short or extremely long internodes was chosen. The F_3 families grown in 1911 are arranged in Table 33 in order of the internode length of the F_2 plants of which they are the progenies as indicated by black-faced figures in the F_3 arrays. The exact reverse in seasonal weather conditions between 1910, when in Nebraska the early summer was favorable for growth and the late summer unfavorable, and 1911, when in Massachusetts the early summer was unfavorable and the late summer very favorable, made it impossible to determine from a single season's study of the F_3 families whether types more extreme than the parents could be isolated. By reference to Table 33 and to Table 39, which latter contains the data for earliness of these same families, it will be noted that, with the marked exception of No. 1137, there was a strong tendency for the early F_3 families to have much shorter internodes and the late families much longer internodes than the F_2 plants of which they were the progenies. In short the early F_2 plants had longer and their F_3 progenies shorter internodes while the late F_2 plants had shorter and their F_3 progenies longer internodes than would have been the case had the weather been more nearly uniform thruout the two seasons.

The parent lots grown in 1911 had, in general, without respect to earliness, shorter internodes than their progenitors of 1910. This is doubtless due to the fact that the parent stocks had been selfed until they had lost much of the vigor acquired thru their former heterozygous condition.

The F_2 families of 1911 are not readily brought into line with the behavior of the F_3 families of the same year. Since they came from different F_1 plants from the F_2 family of 1910 and, therefore, from the F_3 families of 1911, and since these different F_1 plants may have had different internode-length inheritances from the more or less heterozygous parent stocks, it is not strange that their internode length should differ from the F_2 family of the preceding year.

The cross of Missouri dent with California pop (Table 34) gave F_1 progeny with somewhat longer internodes than even the tallest parent had, but the excess was not so great as in case of the cross of Missouri dent and Tom Thumb. In 1910 the mean internode length of F_1 was about 8 mm. greater than that of Missouri dent, 40 mm. greater than that of California pop, and therefore 24 mm. greater than the average of the internode lengths of the parents. Similarly, in 1911 the F_1 families had internodes nearly 8 mm. longer than Missouri dent, nearly 38 mm. longer than California pop, and about 23 mm. longer than the average of the parents. That the long internodes of F_1 are not due to dominance of long over short internodes but rather to increased vigor of growth due to crossing is indicated by the fact that the internode lengths of the F_2 families grown in 1911 were only about 18 mm. greater than those of California pop, about 12 mm. less than those of Missouri dent, and therefore only about 3 mm. greater than the average internode lengths of the parents. Further, if dominance were concerned, the F_2 frequency distributions would be noticeably skewed.

While no F_2 family had quite the combined range of the two parents, the lower extreme of the parents, as grown in 1911, was reached by three F_2 lots and the upper extreme by two. The variation in F_2 was considerably greater than in F_1. There is, therefore, evidence of segregation of internode lengths in F_2 of this cross, as well as in the cross of Missouri dent and Tom Thumb; and here, moveover, the weather must have affected all generations practically alike since they all had about the same season of growth.

TABLE 33.—*Frequency distribution of internode length of plants in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Class centers in millimeters for internode length																Mean	Coef. var.
			54.5	64.5	74.5	84.5	94.5	104.5	114.5	124.5	134.5	144.5	154.5	164.5	174.5	184.5	194.5	204.5		
146	1909	P	......	......	......	......	......	......	......	......	×*									
151	1909	P	......	......	......	×														
170	1909	F1	......	......	......	......	......	......	......	......	......	......	......	×						
363	1910	P	......	......	......	1	1	2	17	22	10	2	1	......	......	......	......	......	122.54 ± 1.04	9.43 ± .60
353	1910	P	......	......	......	3	4	4	5	3	......	......	......	......	......	......	......	......	105.03 ± 2.04	12.54 ± 1.39
357	1910	P	......	......	......	......	2	3	7	11	......	......	......	......	......	......	......	......	116.24 ± 1.35	8.28 ± .82
354	1910	P	......	......	......	1	1	3	7	7	2	1	......	......	......	......	......	......	117.23 ± 1.90	11.26 ± 1.16
358	1910	P	......	......	......	1	3	7	6	4	1	......	......	......	......	......	......	......	109.95 ± 1.72	10.87 ± 1.02
508	1910	P	......	......	1	5	6	3	......	......	......	......	......	......	......	......	......	......	91.83 ± 1.49	9.30 ± 1.15
509	1910	F1	......	......	......	......	......	1	1	3	7	6	2	......	......	......	......	......	135.50 ± 1.84	9.01 ± .96
510	1910	F2	1	1	3	9	19	30	34	33	38	28	15	8	3	1	......	......	123.47 ± 1.03	18.40 ± .61
† 1130	1911	P	......	......	......	......	3	8	8	**1**‡	......	......	......	......	......	......	......	......	108.00 ± 1.20	7.34 ± .79
1148	1911	P	......	......	......	1	......	7	6	**6**	......	......	......	......	......	......	......	......	112.50 ± 1.55	9.15 ± .98
1129	1911	P	......	......	......	......	......	6	17	**14**	3	......	......	......	......	......	......	......	118.00 ± .88	6.98 ± .53
1126	1911	P	......	......	5	8	......	4	**1**	1	......	......	......	......	......	......	......	......	89.76 ± 2.27	16.30 ± 1.83
1127	1911	F2	......	......	......	......	......	2	4	10	11	**17**	17	6	7	1	1	1	146.32 ± 1.51	13.44 ± .74
1128	1911	F2	......	......	......	......	......	2	3	12	**11**	11	19	13	5	4	2	......	148.65 ± 1.50	13.57 ± .73
1139	1911	F3	......	......	......	......	......	**7**	27	38	15	3	......	......	......	......	......	......	122.28 ± .66	7.59 ± .38
1140	1911	F3	......	......	......	......	......	**4**	7	28	26	15	4	1	......	......	......	......	131.20 ± .88	9.16 ± .48
1137	1911	F3	......	......	......	......	......	**0**	6	21	23	8	7	......	......	......	......	......	132.81 ± .92	8.31 ± .50
1141	1911	F3	......	......	......	......	1	7	**23**	40	12	4	......	......	......	......	......	......	122.20 ± .71	8.01 ± .41
1144	1911	F3	......	......	......	......	......	......	**0**	14	36	31	6	......	......	......	......	......	137.83 ± .60	5.99 ± .31
1132	1911	F3	......	......	......	......	2	13	13	**7**	4	1	......	......	......	......	......	......	114.75 ± 1.23	10.03 ± .76
† 1131	1911	F3	......	......	......	......	......	1	8	**26**	22	11	3	......	......	......	......	......	130.56 ± .84	8.08 ± .46
1147	1911	F3	......	......	......	......	......	......	9	**35**	27	7	......	......	......	......	......	......	128.60 ± .62	6.28 ± .34
1143	1911	F3	......	......	......	......	......	3	6	**22**	36	17	3	......	......	......	......	......	132.20 ± .77	8.00 ± .41
1146	1911	F3	......	......	......	......	......	2	9	**23**	32	23	3	1	......	......	......	......	132.89 ± .80	8.50 ± .42
1138	1011	F3	......	......	......	......	......	......	3	9	**17**	17	33	14	2	1	......	......	147.03 ± .98	9.71 ± .48
1135	1911	F3	......	......	......	......	......	1	5	10	**17**	18	21	12	1	......	......	......	143.56 ± 1.11	10.56 ± .55
1149	1911	F3	......	......	......	......	......	......	......	6	**33**	28	8	1	......	......	......	......	139.89 ± .65	5.96 ± .33
1133	1911	F3	......	......	......	......	......	13	14	19	11	**3**	3	1	......	......	......	......	122.94 ± 1.20	11.61 ± .70
1142	1911	F3	......	......	......	......	......	......	2	7	19	**29**	19	6	......	......	......	......	143.52 ± .85	7.97 ± .42
† 1150	1911	F3	......	......	......	3	8	15	11	7	5	**0**	1	......	......	......	......	......	110.70 ± 1.41	13.39 ± .92
1134	1911	F3	......	......	......	......	4	12	12	15	10	**7**	4	......	......	......	......	......	122.63 ± 1.37	13.20 ± .80
1145	1911	F3	......	......	......	......	......	5	9	19	26	13	**9**	......	1	......	......	......	132.43 ± 1.05	10.60 ± .56

* Approximate mean internode length. The range is not known—see text.

† Duplicates.

‡ Black-faced type denotes parent class.

TABLE 34.—*Frequency distribution of internode length of plants in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Class centers in millimeters for internode length										Mean	Coef. var.
			44.5	54.5	64.5	74.5	84.5	94.5	104.5	114.5	124.5	134.5		
353	1910	P					3	4	4	5	3		105.03 ± 2.01	12.54 ± 1.39
499 and 500	1910	P	....	....	4	14	1	....	....	....	....	....	72.92 ± .76	6.70 ± .73
502	1910	F₁						1	10	11	6	...	112.36 ± 1.04	7.28 ± .66
505	1910	F₁	..	....	..	....	....	1	6	10	4	1	113.59 ± 1.29	7.92 ± .81
833	1910	P	....	....	...	5	25	24	28	3	....	....	94.38 ± .73	10.59 ± .55
838	1910	P	..		....	4	7	5	3	....	....	....	88.18 ± 1.52	11.17 ± 1.24
834	1910	P	3	13	21	11	3		....	....	....	..	64.11 ± .92	15.12 ± 1.02
835	1910	P	4	28	18	3	..	..	....	....	....	....	58.27 ± .66	12.12 ± .81
836	1910	F₁	.	..	1	1	6	7	23	3	....		98.89 ± 1.12	10.72 ± .81
837	1910	F₁	....	...	....	2	3	8	14	3	....	....	98.83 ± 1.26	10.35 ± .91
829	1910	F₂	....	3	8	22	37	8	17	....	....	....	83.97 ± .89	15.30 ± .77
830	1910	F₂	1	13	19	31	22	8	1	....	....	....	73.76 ± .85	16.60 ± .83
831	1910	F₂	2	11	17	43	17	3	3	..		....	73.15 ± .81	16.11 ± .80
832	1910	F₂	..	4	27	33	21	8	2	1	....	....	75.75 ± .80	15.27 ± .76
839	1910	F₂	1	2	7	25	27	8	4	....	....	....	80.04 ± .89	14.25 ± .81
840	1910	F₂	....	2	5	11	27	12	14	3	....	....	87.47 ± 1.07	15.58 ± .89

INHERITANCE OF NUMBER OF STALKS PER PLANT.

Missouri dent, like most large dent varieties, tillers very little, producing as a rule only one tall stalk, or at most two stalks, with occasional short tillers. Tom Thumb pop and California pop, on the other hand, produce numerous tillers. Tom Thumb pop usually has one or two principal stalks with several shorter tillers that end in ears instead of tassels. In the California pop most of the numerous tillers have both tassels and ears. In recording the data furnished by crosses of these dent and pop varieties, an attempt was made to distinguish stalks from tillers, but, since the distinction in very many cases was necessarily arbitrary, it is deemed best to count every branch from near the ground as a stalk without regard to its relative length or the presence of a tassel or an ear. Lumping everything in this way does not always bring out the real difference between different families. For instance, No. 1145 is shown in Table 36 to have contained two plants with four stalks each, whereas, as a matter of fact, there was only one plant in the whole lot that had as many as two real stalks. The almost universal condition in this family, as shown in figure 20, was one tall stalk without any tillers or with one or two very short ones. In family 1146, on the other hand, four or five almost equally tall stalks with very rarely a short tiller was the prevailing condition. In many cases, however, all gradations occurred from tall stalks with ears and tassel, tall stalks with tassel but no ear, equally tall stalks ending in an ear instead of in a tassel, etc., to very short branches with neither tassel nor ear. In these cases it was obviously impossible to group the various sorts of branches into two definite classes.

The F_1 of the cross of Missouri dent and California pop, Table 35, was intermediate between the parents in number of stalks per plant both in 1910 and 1911. The range of variation in California pop was greater than in some of the F_2 families. It is quite probable that the stock of this variety used was heterozygous. The F_2 families exhibited more variation than the F_1 families, but only one of them covered the entire range of the parents as grown the same year.

The cross of Missouri dent with Tom Thumb, Table 36, produced F_1's that were intermediate between the parents and F_2's with a range slightly greater than that of the parents combined. That this great variation in F_2 was due to segregation of factors for number of stalks per plant is shown by the F_3 families grown in 1911. These are arranged in the table according to their mean numbers of stalks. Of course, not all of the F_3's were like the F_2 plants from which they came. The modal class of family 1142 was three stalks and the mean number of its stalks a little over two and a half. Evidently its one-stalked F_2 parent was a minus variant of a two-stalked or three-stalked type. Similarly family 1146 had a modal value of five stalks and a mean of about four and a quarter, while its F_2 parent had only three stalks, and 1149 had a mean of only about two stalks, tho its F_2 parent had four. Family 1139, whose F_2 parent also had four stalks, had a mean of nearly four and a quarter stalks. The four stalks of the parent of 1149, however, consisted of one main stalk and three rather short suckers, while all the four stalks of the parent of 1139 were tall. That this difference, tho possibly significant, cannot be relied upon is shown by the fact that families 1132 and 1140, the F_2 parents of which, like that of 1149, had only one stalk and three suckers, had four stalks as their modal class and between three and four stalks as their means.

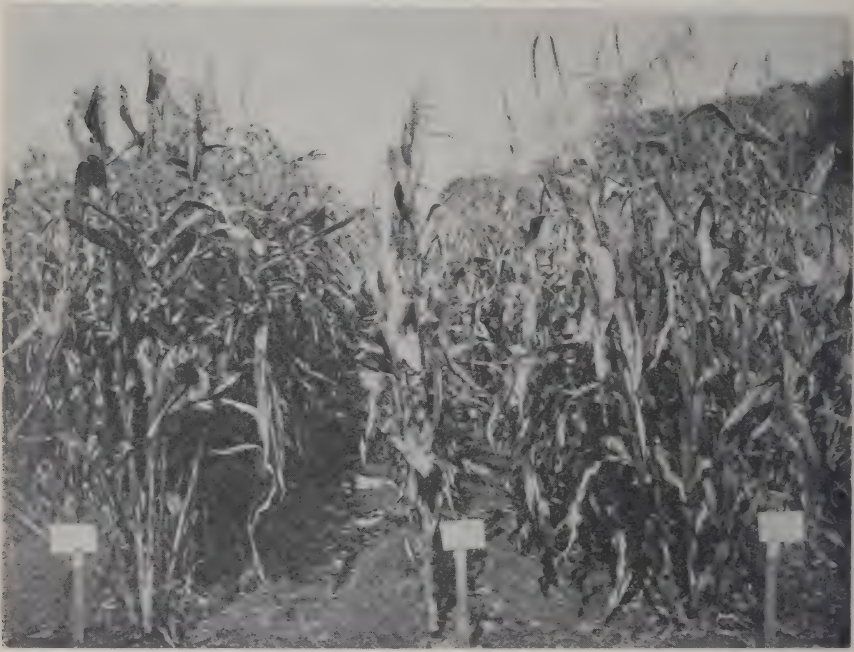

Fig. 19. Three F_3 families of Tom Thumb pop × Missouri dent showing marked differences in number of tillers. September 19, 1911.

The most significant fact established by these F_3 families as a whole is that from the segregates of F_2 were produced types with various numbers of stalks ranging from one parent type to the other. In forming an idea of the types represented by the parent

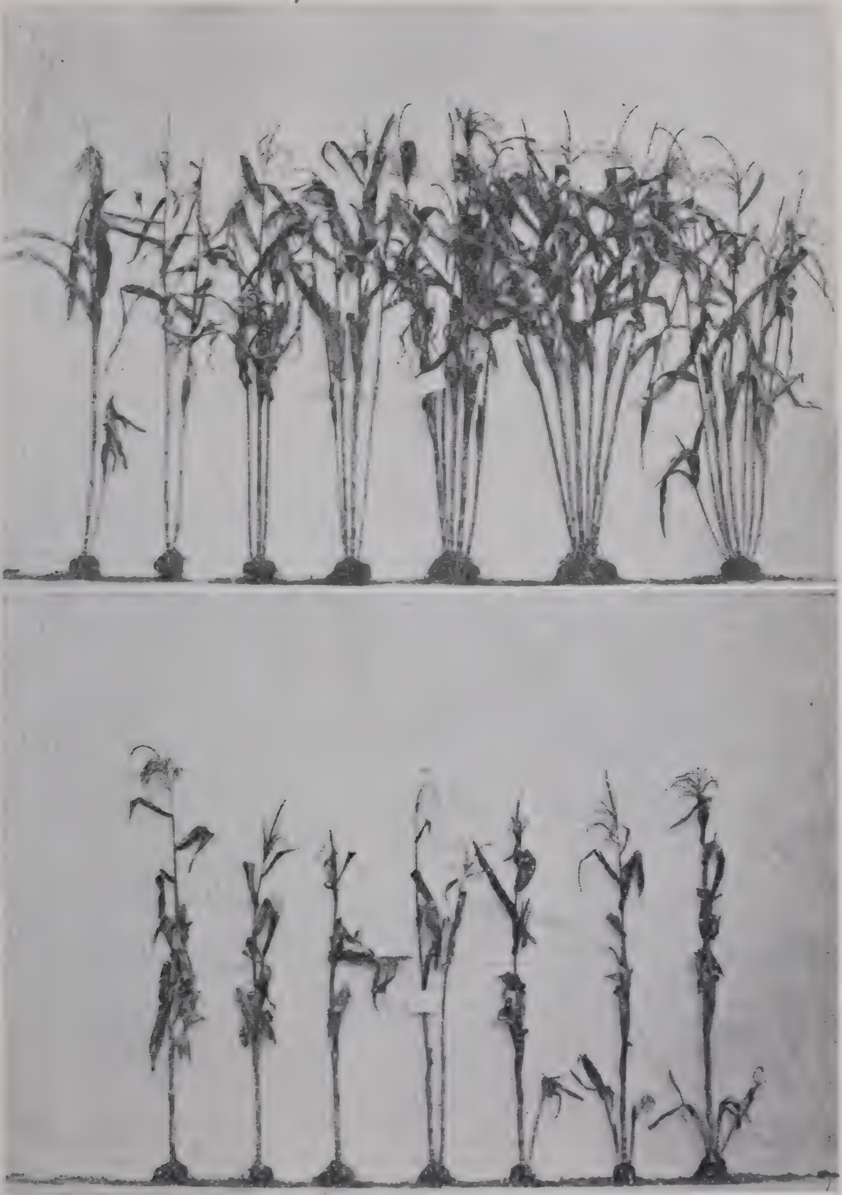

Fig. 20. Representative plants of two F_3 families of Tom Thumb pop × Missouri dent. The lower leaves were removed to show the number of stalks per plant.

varieties, the frequency distributions for 1909 and 1910 are perhaps more useful than those of 1911. While the 1911 stocks of these varieties were doubtless more nearly homozygous than the stocks of previous years, they probably did not possess just the factors carried by the two germ cells whose union resulted eventually in the 1911 F_3 families. Approaching homozygosis of other factors as well as of size factors rendered the 1911 parent stocks less vigorous than they were in previous years and thereby lessened the tendency to tiller, somewhat as poor or dry soil is known to do. The very few tillers produced by the 1911 stock of Tom Thumb, No. 1126, was due in part perhaps to this cause, in part to the very unfavorable weather conditions while it was developing, and doubtless in part also to the isolation of a type with comparatively few stalks.

Whether any of the F_3 lots of this cross were homozygous for all the factors that have to do with number of stalks cannot be determined without further breeding. It seems probable that some of them, like 1145 for instance, that had a small range of variation will be found to breed practically true, while from others it will perhaps be possible to isolate several types.*

Among the F_3 families of Tom Thumb × Black Mexican there was a noticeable difference in number of stalks per plant. Two families scarcely ever tillered, while one family averaged four tillers per plant.

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* While some intimation of what the future behavior of any F_3 family will be may perhaps be obtained from an inspection of the range of variation and from the statistical constants, particularly the standard deviation, too much dependence cannot be put upon these things. It may be, as was suggested earlier for number of rows per ear, that types of plants with an inherently large number of stalks naturally fluctuate more than types with an inherently small number of stalks because each inherent stalk may furnish a basis for fluctuation. From this point of view, the coefficient of variation seems a better measure of relative fluctuation than does the standard deviation, because it expresses the deviation as a percentage of the thing that deviates. From an inspection of the arrays (Table 36) and even more from an inspection of the plants themselves, it would, however, be difficult to believe that family 1146 is less variable than family 1145, even tho the coefficients of variation are 29.86 ± 1.60 per cent for the former and 48.31 ± 3.08 per cent for the latter. The standard deviations of these families are respectively 1.27 ± .06 and 0.80 ± .04 stalks. Only further breeding experiments, rather than statistical constants, can show how much of this variation in either case is mere fluctuation and how much due to genetic differences.

TABLE 35.—*Frequency distribution of number of stalks per plant in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Classes for number of stalks per plant											Mean	Stand. dev.	Coef. var.
			1	2	3	4	5	6	7	8	9	10	11			
353	1910	P	2	5	9	5	1	...	...	...	...	...	...	2.91 ± .14	1.00 ± .10	34.26 ± 3.84
499 and 500	1910	P	...	...	...	1	1	1	2	2	7	3	2	8.42 ± .29	1.85 ± .20	21.91 ± 2.41
502	1910	F$_1$	...	...	6	16	10	3	2	...	...	...	...	4.43 ± .11	1.03 ± .08	23.14 ± 1.91
505	1910	F$_1$	...	...	7	5	3	4	2	...	...	...	...	4.48 ± .20	1.37 ± .14	30.51 ± 3.47
833	1911	P	69	12	4	...	...	...	...	...	...	...	...	1.24 ± .04	.53 ± .03	42.42 ± 2.56
838	1911	P	3	6	4	5	1	...	...	...	...	...	...	2.74 ± .18	1.16 ± .13	42.48 ± 5.19
834	1911	P	...	...	1	5	17	13	11	3	1	...	...	5.80 ± .12	1.22 ± .08	21.05 ± 1.47
835	1911	P	1	1	2	7	7	13	13	7	2	...	...	5.94 ± .16	1.70 ± .11	28.57 ± 2.02
836	1911	F$_1$	1	1	5	16	16	1	1	...	...	...	...	4.27 ± .11	1.03 ± .08	24.22 ± 1.91
837	1911	F$_1$	...	...	9	16	4	1	...	...	...	...	...	3.90 ± .09	.74 ± .07	19.08 ± 1.71
829	1911	F$_2$	5	19	29	29	9	3	...	...	...	...	...	3.29 ± .08	1.14 ± .06	34.74 ± 1.90
830	1911	F$_2$	14	14	41	18	7	1	...	...	...	...	...	2.93 ± .08	1.14 ± .06	39.01 ± 2.18
831	1911	F$_2$	6	7	14	29	25	11	3	1	...	...	...	4.15 ± .10	1.46 ± .07	35.25 ± 1.92
832	1911	F$_2$	3	6	36	29	16	4	1	...	1	...	...	3.74 ± .09	1.24 ± .06	33.05 ± 1.78
839	1911	F$_2$	21	19	26	12	1	...	...	...	...	...	...	2.41 ± .08	1.07 ± .06	44.56 ± 2.83
840	1911	F$_2$	20	17	22	13	2	...	...	...	...	...	...	2.46 ± .09	1.14 ± .06	46.38 ± 3.08

TABLE 36.—*Frequency distribution of number of stalks per plant in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Parent class	Classes for number of stalks per plant								Mean	Stand. dev.	Coef. var.
				1	2	3	4	5	6	7	8			
146	1909	P		81	9	7	1					1.27 ± .04	.63 ± .03	49.53 ± 2.91
151	1909	P				2	3	1				3.83 ± .18	.66 ± .13	17.31 ± 3.47
170	1909	F_1			16	13	5	1				2.74 ± .09	.81 ± .07	29.45 ± 2.56
363	1910	P		4	18	21	13	2				2.85 ± .09	.96 ± .06	33.68 ± 2.36
353	1910	P		2	5	9	5	1				2.91 ± .14	1.00 ± .10	34.26 ± 3.84
357	1910	P		10	6	4	2	1				2.04 ± .16	1.16 ± .12	56.81 ± 7.23
354	1910	P		7	12	6						1.96 ± .10	.72 ± .07	36.68 ± 3.94
358	1910	P		11	8	6						1.80 ± .11	.80 ± .08	44.44 ± 5.01
508	1910	P				3	10	1	1			3.67 ± .14	.80 ± .10	21.85 ± 2.83
509	1910	F_1				7	13					3.65 ± .07	.47 ± .05	12.99 ± 1.41
510	1910	F_2		20	18	59	75	46	4		1	3.57 ± .06	1.25 ± .04	34.87 ± 1.24
* 1130	1911	P	4	9	5	5	1					1.90 ± .14	.94 ± .10	49.63 ± 6.46
1148	1911	P	4	11	5	4	0					1.65 ± .12	.79 ± .08	47.94 ± 6.18
1129	1911	P	3	38	2	0						1.05 ± .07	.67 ± .05	63.90 ± 6.51
1126	1911	P	3	7	6	6						1.95 ± .13	.82 ± .09	42.26 ± 5.41
1127	1911	F_2	4	16	22	20	15	4				2.60 ± .09	1.17 ± .06	44.81 ± 2.90
1128	1911	F_2	3	11	26	16	17	8	3	1		2.98 ± .11	1.41 ± .07	47.15 ± 2.98
1145	1911	F_3	1	43	26	11	2					1.66 ± .06	.80 ± .04	48.31 ± 3.08
* 1131	1911	F_3	1	31	21	15	4					1.89 ± .07	.93 ± .05	49.00 ± 3.38
1147	1911	F_3	1	26	20	22	9	1				2.22 ± .08	1.07 ± .06	48.24 ± 3.15
1149	1911	F_3	4	31	16	24	5					2.04 ± .08	.99 ± .05	48.63 ± 3.23
1143	1911	F_3	1	28	16	33	9	1				2.30 ± .08	1.06 ± .05	46.22 ± 2.82
* 1150	1911	F_3	2	13	12	17	7	1				2.42 ± .10	1.08 ± .07	44.63 ± 3.56
1134	1911	F_3	2	17	11	24	10	2				2.52 ± .10	1.13 ± .07	44.88 ± 3.18
1142	1911	F_3	1	15	19	29	19					2.63 ± .08	1.03 ± .05	39.24 ± 2.34
1133	1911	F_3	5	8	11	17	23	5				3.09 ± .10	1.16 ± .07	37.41 ± 2.52
1141	1911	F_3	4	12	9	27	25	11	3			3.26 ± .09	1.30 ± .07	39.88 ± 2.34
1138	1911	F_3	2	7	12	29	33	13	2			3.41 ± .08	1.15 ± .06	33.78 ± 1.82
1135	1911	F_3	4	3	18	22	30	11	1			3.36 ± .08	1.09 ± .06	32.56 ± 1.85
1140	1911	F_3	4	7	11	24	27	15		1		3.42 ± .09	1.22 ± .06	35.73 ± 2.08
1137	1911	F_3	5	5	5	18	27	8	2			3.52 ± .10	1.14 ± .07	32.33 ± 2.10
1144	1911	F_3	3	4	2	28	37	14	2			3.70 ± .07	1.00 ± .05	26.92 ± 1.47
1132	1911	F_3	4	1	3	10	17	8	1			3.78 ± .11	1.01 ± .08	26.80 ± 2.16
1139	1911	F_3	4	2	7	11	30	30	10			4.21 ± .08	1.17 ± .06	27.72 ± 1.49
1146	1911	F_3	3	1	8	18	21	34	9	1	1	4.24 ± .09	1.27 ± .06	29.86 ± 1.60

* Duplicates.

INHERITANCE OF TOTAL LENGTH OF STALKS PER PLANT.

For the studies of height of plants, only the main stalk of each plant was measured and for the studies of number of stalks per plant every stalk, whether tall or short, was counted. Neither of these sets of data gives a very good idea of the total amount of stalk produced. While it certainly would have been desirable to determine the dry weight of each plant, that could not be done. Doubtless a fair notion of the amount of substance per plant could be obtained from a knowledge of the total length and average diameter of stalks per plant, but no determinations of diameters were made. The only measurements of total length of stalks were made in 1911. The data are given in Tables 37 and 38.

Table 37 affords a comparison of Missouri dent, California pop, and F_1 and F_2 generations of a cross of these varieties. While the different families of the same parent or hybrid generation differed considerably from one another, there were also fairly well marked differences between the different generations. The short-stalked California pop, Nos. 834 and 835, owing to its large number of stalks per plant, had a greater total length of stalk per plant than did the much taller Missouri dent, Nos. 833 and 838. The increased vigor of the F_1 generation, Nos. 836 and 837, resulted in a total length of stalk considerably greater than that of either parent. None of the F_2 families had an average total length of stalk equal to F_1 nor did any of them much exceed the California pop parent in this respect. Some of the F_2 families, however, equaled in range of variation the combined range of the parents and F_1. Whether a type breeding true to a total stalk length greater than that of either parent could be isolated by selection from among the F_2's can be told only by further breeding.

Similar data for the cross of Missouri dent and Tom Thumb pop are presented in Table 38. No F_1 generation of this cross was grown in 1911, but the parent and F_2 generations will serve for comparison with the various F_3 families. The unfavorable early season and previous inbreeding combined to make the total length of stalk of Tom Thumb pop, No. 1126, unusually small, only about one-fifth that of Missouri dent, Nos. 1129, 1130, and 1148. The average total length of stalks of the F_2 families, Nos. 1127 and 1128, equaled or exceeded somewhat that of the Missouri dent parent. The range of variation in F_2 was considerably greater than in the parents. In some of the F_3 families the range of variation was even greater than in F_2, while in others it was little if any greater than in the parent varieties. The mean total length of stalk of the F_3 families varied from about midway between the parents to somewhat over twice that of the larger parent. (Compare Nos. 1133 and 1145 with 1144 and 1146.) While of course the Missouri dent stock grown in 1911 did not produce as tall stalks as it doubtless would have done if it had not been previously selfed, it is quite unlikely that any cross-pollination within the original stock would have resulted in a type like family 1146. The cross of a tall, few-stalked variety with a short, many-stalked sort has resulted in the production of a tall many-stalked type quite unlike either parent.

TABLE 37.—*Frequency distribution of total length of stalks in cross between California pop and Missouri dent.*

Designation	Year	Gen.	Class centers in decimeters for total length of stalks											Mean	Coef. var.
				15	25	35	45	55	65	75	85	95	105		
833	1911	P	......	58	17	6	4	......	......	......	......	......	......	19.82 ± .60	41.40 ± 2.48
838	1911	P	......	3	3	7	2	2	1	1	......	......	......	37.11 ± 2.46	42.81 ± 5.06
834	1911	P	......	1	7	15	15	9	4	......	......	......	......	42.06 ± 1.13	28.36 ± 1.97
835	1911	P	1	2	7	14	16	11	2	......	......	......	......	40.66 ± 1.17	31.15 ± 2.23
836	1911	F_1	......	2	......	......	5	7	9	7	7	4	......	66.46 ± 2.00	28.49 ± 2.29
837	1911	F_1	......	......	......	2	8	7	8	3	1	1	......	58.00 ± 1.72	24.03 ± 2.22
830	1911	F_2	......	18	20	24	19	12	2	......	......	......	......	34.26 ± .94	39.78 ± 2.23
839	1911	F_2	......	25	11	14	16	8	......	......	......	......	......	31.08 ± 1.11	45.45 ± 3.00
840	1911	F_2	1	19	15	14	13	8	4	......	......	......	......	32.97 ± 1.22	47.04 ± 3.23
829	1911	F_2	......	8	14	21	26	16	7	2	1	......	......	41.53 ± 1.04	36.52 ± 2.01
831	1911	F_2	1	10	12	14	25	14	13	6	......	1	......	44.06 ± 1.24	40.91 ± 2.30
832	1911	F_2	......	4	13	25	22	15	12	3	1	......	1	44.48 ± 1.12	36.62 ± 2.01

TABLE 38.—*Frequency distribution of total length of stalks in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Class centers in decimeters for total length of stalks														Mean	Stand. dev.	Coef. var.
			4.5	14.5	24.5	34.5	44.5	51.5	64.5	74.5	84.5	94.5	104.5	114.5	124.5	134.5			
1129	1911	P	......	2	36	......	2	......	......	......	......	......	......	......	......	......	25.00 ± .53	4.98 ± .38	19.90 ± 1.56
* { 1130	1911	P	......	1	10	2	4	2	......	1	......	......	......	......	......	......	34.50 ± 2.19	14.49 ± 1.55	42.00 ± 5.21
{ 1148	1911	P	......	1	10	2	4	1	2	......	......	......	......	......	......	......	34.50 ± 2.13	14.14 ± 1.51	40.99 ± 5.13
1126	1911	P	15	4	......	......	......	......	......	......	......	......	......	......	......	......	6.61 ± .63	4.08 ± .45	61.68 ± 8.98
1127	1911	F2	......	12	27	18	7	6	2	3	1	1	......	......	......	......	34.11 ± 1.34	17.39 ± .95	50.98 ± 3.58
1128	1911	F2	......	12	18	16	9	11	6	6	1	......	3	......	......	......	41.45 ± 1.65	22.12 ± 1.17	53.37 ± 3.51
1133	1911	F3	......	28	26	10	......	......	......	......	......	......	......	......	......	......	21.69 ± .61	7.17 ± .43	33.08 ± 2.18
1145	1911	F3	......	21	53	6	2	......	......	......	......	......	......	......	......	......	23.16 ± .48	6.39 ± .34	27.61 ± 1.56
1132	1911	F3	......	10	14	12	3	1	......	......	......	......	......	......	......	......	27.25 ± 1.07	9.99 ± .75	36.67 ± 3.11
* { 1134	1911	F3	......	35	14	8	4	3	......	......	......	......	......	......	......	......	22.94 ± 1.57	11.49 ± .69	50.07 ± 3.66
{ 1150	1911	F3	2	18	16	5	6	......	2	......	......	1	......	......	......	......	26.50 ± 1.56	16.37 ± 1.10	61.78 ± 5.53
* { 1131	1911	F3	......	5	37	10	8	7	3	......	1	......	......	......	......	......	32.95 ± 1.14	14.21 ± .80	43.11 ± 2.86
{ 1147	1911	F3	......	1	28	16	15	9	4	3	2	......	......	......	......	......	39.24 ± 1.22	15.99 ± .86	40.75 ± 1.54
1143	1911	F3	......	4	30	19	16	8	5	1	4	......	......	......	......	......	38.29 ± 1.21	16.70 ± .85	43.63 ± 2.63
1142	1911	F3	......	11	15	13	11	16	10	3	......	......	......	......	......	......	40.72 ± 1.28	17.22 ± .91	42.30 ± 2.60
1149	1911	F3	......	......	32	5	17	13	5	3	......	1	......	......	......	......	40.29 ± 1.27	16.41 ± .90	40.72 ± 2.57
1135	1911	F3	......	4	17	23	15	13	11	1	1	......	......	......	......	......	41.32 ± 1.12	15.36 ± .79	37.16 ± 2.17
1137	1911	F3	......	5	3	14	16	15	8	3	1	......	......	......	......	......	45.88 ± 1.31	15.68 ± .93	34.17 ± 2.24
1140	1911	F3	......	1	11	13	25	15	10	5	3	1	......	......	......	1	48.97 ± 1.38	18.88 ± .98	38.56 ± 2.27
1141	1911	F3	......	6	8	7	15	13	17	9	4	5	2	1	......	......	55.19 ± 1.67	23.13 ± 1.18	41.92 ± 2.49
1138	1911	F3	......	1	10	11	15	8	15	14	13	4	4	1	......	......	60.02 ± 1.61	23.36 ± 1.14	38.92 ± 2.16
1139	1911	F3	......	2	8	6	10	7	23	11	10	6	6	1	......	......	63.50 ± 1.68	23.67 ± 1.19	37.27 ± 2.12
1144	1911	F3	......	......	5	1	7	13	22	16	10	7	3	2	1	......	68.52 ± 1.49	20.59 ± 1.05	30.05 ± 1.67
1146	1911	F3	......	......	3	3	4	14	11	8	13	17	9	3	6	2	79.88 ± 1.82	26.05 ± 1.29	32.61 ± 1.78

* Duplicates.

INHERITANCE OF DURATION OF GROWTH.

While the time required for a corn plant to reach a definite stage in its development, such as blossoming or ripening, is not strictly a size character, it has nevertheless a marked influence upon the size of plants or plant parts. It has been pointed out earlier in this paper how earliness and lateness may affect the height of plants if the season is more favorable at one time than at another. Besides this effect it is reasonable to expect a physiological correlation between size and duration of growth. Obviously an extremely early plant cannot in its few weeks of growth attain a height equal to that ultimately reached by another plant whose period of growth extends thruout the entire summer. It does not follow from this, however, that there is any genetic correlation between duration of growth and ultimate size. Later in this paper we shall consider this point further.

The general average difference between times of flowering in various F_3 families of Tom Thumb × Black Mexican was very marked. Family (60-3x54)1-2AS was two weeks earlier than (60-8x54)8-8CS.

The cross of Tom Thumb pop with Missouri dent furnished favorable material for a study of the inheritance of length of growing period. Missouri dent is so late that it barely ripens at Lincoln, Nebraska, while Tom Thumb pop is one of the earliest varieties known. In 1910 both varieties were planted together on the same day and ripe ears of Tom Thumb pop were harvested the same day that some of the Missouri dent plants were pollinated.

The two dates that perhaps best measure the duration of the growing period are the date of planting and the date of ripening of the ears. It is difficult, however, to tell exactly when an ear is ripe. Hardness of kernels and dryness of the outer husks were taken to indicate ripeness, but it can never be said that the husks were green yesterday and are dry today. The date of blossoming can be fixed much more definitely than the date of ripening, but growth has not ceased at this time. The ears, in fact, make their principal growth after blossoming. The growth in height of stalks, however, is practically complete at blossoming time, so that this date and the planting date can be used to determine roughly the period of height growth. Moreover, there is a more or less definite relation between the time required by a corn plant to reach the blossoming stage and the time required by it to reach full maturity. The former is usually not far from sixty per cent of the latter. In case of a large-eared variety, the period of blossoming to maturity is likely to be relatively longer than in case of a small-eared sort. For instance, the large-eared

Missouri dent and the very small-eared California pop blossom almost together, but the latter ripens some days ahead of the former. Again, a very early corn may have its later stages shortened relatively by the heat of midsummer, while a very late variety may have its ripening stage relatively prolonged by the cooler weather of autumn.

In 1910 the date of ripening of each plant of the cross under consideration—Tom Thumb × Missouri dent—was determined as closely as practicable, while the dates of blossoming were noted for only such plants as were hand-pollinated. The various lots were examined carefully on the same day each week and all plants deemed ripe were noted. Since in 1911 this corn was grown in Massachusetts, it was foreseen that the later families could not possibly ripen, and, therefore, blossoming dates alone were recorded. The time of the exposure of the first anthers of the tassel on the main stalk was chosen as the date of blossoming. In the case of protandrous plants, which constituted the bulk of those grown, this was the only date recorded, but for the few protogynous families the date of exposure of the first silks was also noted. The entire lot of plants was examined each day and those just beginning to blossom were tagged. The available data are grouped together in Table 39. Since in 1910 the dates of ripening were taken weekly while the dates of blossoming are arranged in three-day classes, only the range of variation of the 1910 families is shown in the table. Since the blossoming dates of hand-pollinated plants only were recorded in 1910, the ranges of variation indicated in the table are not necessarily the complete ranges of blossoming dates. A large majority of the plants, however, blossomed within the dates shown in the table. The class headings indicate the number of days from planting to blossoming or ripening.

In 1910, Tom Thumb pop (family 508) was in blossom 60 to 70 days from planting time, while Missouri dent (353) was blossoming 85 to 95 days after planting. The F_1 plants (509) were distinctly intermediate, with a blossoming time of 73 to 83 days from planting. Some of the F_2 plants (510) were nearly as early as the earliest Tom Thumb pop plants, while others were almost as late as the latest Missouri dent. The F_3 blossoming time extended over a period of thirty days, 62 to 92 days after planting. The 1910 families held the same relative order in ripening as in flowering. The parent varieties were farther apart in ripening than in blossoming, Missouri dent having ripened in 144 to 151 days and Tom Thumb pop in 91 to 98 days, or while Missouri dent was still in flower. The F_1 plants were somewhat later than half way between the parents, with ripening dates 122 to 136 days after planting. The earliest F_2

plants were ripe soon after the latest F_2's were in blossom. The period of ripening extended between seven and eight weeks, or 94 to 146 days from planting.

As grown in Massachusetts in 1911, Tom Thumb pop (1126) had an average blossoming date (staminate flowers) of about 64 days from planting, or practically the same as in Nebraska the year before. Missouri dent (1129, 1130, 1148), on the other hand, was about fifteen days later than the previous year, its average flowering date having been about 105 days from planting. The comparatively cool weather of midsummer and later was doubtless responsible for the delay in case of Missouri dent, while the heat of early summer—unprecedented in Massachusetts—brought Tom Thumb pop into flower as early as in Nebraska the year before. No F_1 plants were grown in 1911. The two F_2 families (1127, 1128), tho containing fewer individuals than the F_2 family of 1910, nevertheless showed a somewhat greater range of variation. It is possible that the same conditions which made Missouri dent later than in 1910 and forced Tom Thumb pop into flower as early as in 1910 tended to extend the F_2 range considerably. Notwithstanding this, the latest F_2 plants were in flower when the earliest Missouri dent plants began blossoming.

The F_3 progenies, all grown in 1911, were of course subject to the same climatic influence as the parents and F_2. Apparently, however, no F_3 family responded to this influence quite as Missouri dent did. The parents of some F_3 families were among the latest tho not the very latest F_2 plants, as indicated in Table 39. (The blossoming time of the parent of each F_3 family is shown in the table by black-faced type in the corresponding F_3 class.) It was expected that some of the F_3 lots would, therefore, be almost if not quite as late as Missouri dent. None of them, however, had an average blossoming date later than 87.5 days from planting, while the average date of flowering of the earliest Missouri dent family was nearly 13 days later. It is probable that some of the plants chosen from among the later F_2's of 1910 were plus variates of only medium late types,—for their F_3 progenies, notwithstanding the cooler weather of the late summer of 1911, were considerably earlier than they were in 1910. This was particularly noticeable in case of families 1140, 1142, 1145, and 1146. The parent of family 1145, for instance, blossomed about 88 days after planting, while not a single plant of 1145 was quite so late as that, and the average date of flowering for the family was only a little over 73 days. Families 1149 and 1131 and the latter's duplicate 1147, on the other hand, were from F_2 plants that blossomed in 1910 about 85 days after planting, and their average date of blossoming in 1911 was almost the same, 86 days from planting.

That neither of the F_2 families and none of the F_3's had any plants that were as late as the Missouri dent plants of 1911 is perhaps not strange when it is remembered that the original parent plants were representatives of commercial strains which had not been previously self-pollinated and when it is also recalled that the lots representing the two parent varieties were not descended directly from the plants used as parents of the cross. That the parent varieties were heterozygous for time of blossoming as well as for various other characters is indicated by the fact that one of the lots grown in 1911 was considerably earlier than the other. It is possible that the single gamete from Missouri dent, which by union with a gamete from Tom Thumb pop gave rise to F_2 family 510 and to all the F_3 families, lacked some of the factors for long-continued growth that were present in the parents of the lots used later to represent Missouri dent. It might further be supposed that the 1910 representatives of Missouri dent were forced into abnormally early blossoming by the hot dry weather of that summer. It would then still remain to be explained why the weather of 1910 in Nebraska should make Missouri dent plants unusually early and at the same time cause many of the later F_2 plants to be unusually late, as was assumed before. Or perhaps it will be as necessary to explain why the weather of 1911 in Massachusetts delayed the blossoming of Missouri dent and at the same time hastened the blossoming of the later F_3 families.

In this connection it should not be forgotten that too high a temperature, particularly if associated with extreme dryness, may retard the development of plants not adapted to such conditions while hastening the development of other sorts of plants. We do not know that diverse sorts of corn actually respond in these different ways to unusual conditions, but the possibility is worth considering. Is it possible that an early corn like Tom Thumb pop, adapted to growth in the North, may develop quite as rapidly at moderate temperatures as at higher ones, *i. e.,* the optimum temperature for it is low, while a late variety, which can only be matured in the South, may be greatly retarded in its development by anything short of high temperatures? And is it possible also that this assumed adaptation to growth at somewhat low temperatures might be inherited independently of other genetic factors for earliness, so that F_2 segregates might rank quite differently in earliness in different seasons? The topic should not be dismissed without referring back to the records of height of plant of these same lots of corn (Table 29). Here we meet the suggestive facts, *first*, that the 1911 Missouri dent families were not so tall as the 1910 plants from which they came, tho it took them much longer to complete their growth, and, *second*, that certain of the 1911 F_3 families were taller than their 1910 F_2 parents, tho they required less time to complete their growth. It would seem that sometimes, at least, the conditions that hasten development are favorable to a large height growth while the conditions that prolong growth unduly are unfavorable to great height growth. Since the soil and weather conditions to which the Missouri dent and F_2 plants were subjected in 1910 were practically the same for both lots and since the same was true for the Missouri dent and F_3 families in 1911, the markedly different behavior of the two lots in the two seasons was due obviously to an inherent difference between the two lots of plants—a difference in the way they responded to like environments. Whether this difference may have been as was suggested above, a matter of different optimum temperatures for the two lots, or whether the more nearly complete homozygosis of Missouri dent than of the other lots may have been a controlling factor, cannot now be said. It is easy to see that Missouri dent may have had shorter stalks in 1911 than in 1910, notwithstanding the moister conditions of the latter season, because of repeated selfing, and that it may have been later in 1911 than the year before because of the cooler weather. The 1911 F_3 families might then have had taller stalks than their 1910 parents because of the moister conditions in 1911. It certainly could not have been due to a greater degree of heterozygosity. But why were they earlier under the cooler conditions surrounding them in 1911 than were their F_2 parents under the hotter conditions of 1910, unless the optimum temperature for them is lower than for Missouri dent?

While there are, then, numerous difficulties to be met before a satisfactory explanation can be given of some of the facts brought out in this study of the inheritance of duration of growth, they should not be permitted to obscure the simple facts that a cross of a very early variety of corn with a very late variety produced an F_1 generation strictly intermediate between the parents in earliness, F_2 generations with a range of variation from the early parent to, or nearly to, the late parent, and F_3 generations with diverse seasons of blossoming. From Table 39 it can be seen that the latest F_3 family blossomed on the average a little over three weeks later than the earliest F_3 family and that the earliest three F_3 families were all but out of flower before the latest three began blossoming. The impression of distinct difference in earliness made by the plants in the field was even more vivid than that made by the figures in the table. The photograph reproduced in this paper (figure 21) gives some indication of the differences as they appeared in the field.

There is one other feature of this study of time of blossoming that should be noted. The strain of Tom Thumb pop employed in these tests was strongly protogynous as seen from Table 39, where the frequency distribution of days to first exposure of silks in case of protogynous families is shown in italics immediately below the frequency distributions for days to first shedding of pollen for the same families. Of Tom Thumb pop (family 1126), the plants showed their silks from one to eight days earlier and on the average four days earlier than the first shedding of pollen. The Missouri dent used was evidently heterozygous for this condition, since one 1911 lot (family 1129) was protandrous thruout while the other lot (family 1130 and its duplicate 1148) was protogynous thruout, all but three plants of the latter having had their silks first exposed from one to six days and on the average just three days before any pollen was shed. Both of the F_2 families grown in 1911 (1127

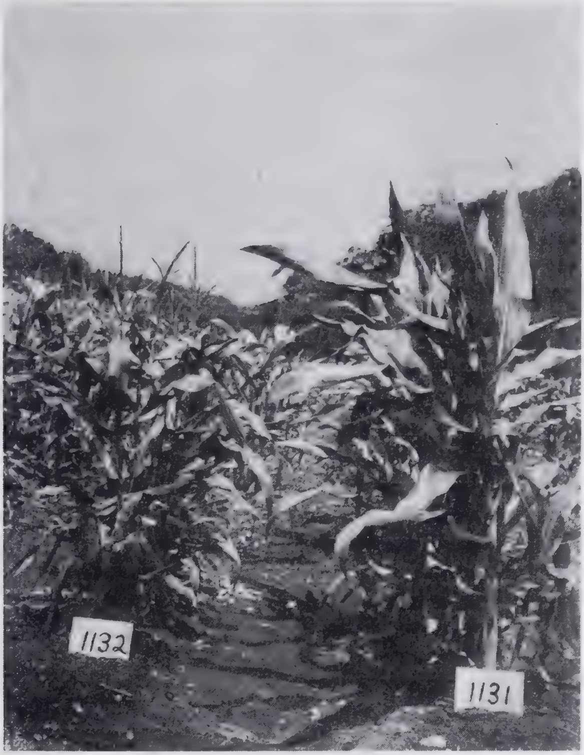

Fig. 21. Two F_3 families of Tom Thumb × Missouri dent as they appeared in the field July 26, 1911. Note difference in earliness.

and 1128) were wholly protandrous. Some plants of the 1910 F_2 lot (family 510) were observed to be protogynous but no adequate records were made of that family. Only one F_3 family (1132) contained protogynous plants. Of this family twenty-eight plants were protandrous and only twelve protogynous. Of the latter the silks began to show from one to three days and on the average about two days earlier than the pollen began to shed.

Had the time of exposure of the first silks instead of the time of shedding of pollen been taken as the date of flowering for all of the families, family 1132 would have been classed as even earlier and all the other F_3 families somewhat later than they were, for in protandrous corn the silks usually appear from one to four or five days after the pollen begins to shed. If protandry is regarded as the normal condition, because it is the most common, protogyny may be thought of as delayed development of the staminate flowers, in which case the time of exposure of the silks would better be used as the date of flowering, or it may be thought of as precocious development of the pistillate flowers, in which case the time of opening of the anthers would better be taken as the blossoming date. Or in case protogyny is considered normal and protandry abnormal, the latter may be regarded as delayed development of the pistillate flowers or as the precocious development of the staminate flowers. In the first case the silks and in the second the anthers would be the better index of flowering. The fact that in protogynous types of corn, so far as they are known to us, the silks protrude from the leaf sheath before the ear-bearing shoot has appeared may perhaps be rightly regarded as an indication of precocious development of the pistillate flowers. This would place protogyny as an "abnormal" character and make the staminate flowers the better guide in fixing the date of flowering. It is probable, however, that both protogyny and protandry are quite normal.

No attempt has been made as yet to study the inheritance of protogyny or protandry as definite characters. It is possible that they are mere chance relations between times of maturity of pistillate and staminate flowers. If so, however, there must be a pronounced physiological correlation between time of maturing of the two sorts of flowers, for otherwise any lot of corn with a considerable range of variation in time of flowering would by chance show all gradations from strong protandry to strong protogyny with slight protandry or protogyny or even homogamy as the modal condition. It is also likely that there is genetic correlation between the time of maturity of the staminate and pistillate flowers and that this is in fact the only basis for considering protogyny and protandry as definite characters. If there were

TABLE 39. *Frequency distribution of number of days from planting to flowering and ripening in cross between Tom Thumb pop and Missouri dent.*

Designation	Year	Gen.	Class centers in days to flowering and ripening																																			Mean		Coef. var.	
			49	52	55	58	61	64	67	70	73	76	79	82	85	88	91	94	97	100	103	106	109	112	115	118	121	124	127	130	133	136	139	142	145	148	151				
[illegible]																																									
[illegible]																																									
[illegible]																																									
[illegible]																																									
[illegible]	1911	P					[illegible]	6	[illegible]	[illegible]																												63.81	.46	4.69	.51
1126																																									
[illegible]	1911	P															***2***	5	[illegible]	[illegible]	[illegible]	2	1	[illegible]														101.45	.64	[illegible]	[illegible]
* [illegible]	[illegible]	P																0			[illegible]	4	6	2	2	1												108.25	.65	[illegible]	[illegible]
1130																									*1*																
1118	1911	P																0		1	[illegible]	[illegible]	[illegible]	1		1												106.90	.56	[illegible]	[illegible]
1118																		*1*	*1*																						
[illegible]	[illegible]	[illegible]					7	8	14	4	6	**5**	10	7	6	4	2	**3**																				74.32	.73	12.82	.70
[illegible]	[illegible]	[illegible]					4	14	10	15	5	13	**5**	4	7	4	1																					72.85	.59	10.78	.57
[illegible]	[illegible]	[illegible]					12	**12**	4	10	1	1																										65.43	.43	6.15	.46
[illegible]							*9*	*7*	*6*	*7*	*6*	*1*																													
[illegible]	[illegible]	[illegible]				1	16	14	**12**	12	4	2																										[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]					6	20	16	8	7	2																										[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]					2	15	**6**	10	9							1																				[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]					10	20	**19**	15	9	[illegible]																										[illegible]		[illegible]	[illegible]
[illegible]	1911	[illegible]					8	22	14	**11**	4	[illegible]	2																									[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]					1	3	12	12	13	[illegible]	17	11	7	[illegible]																								[illegible]	[illegible]
[illegible]	[illegible]	[illegible]						7	12	17	9	16	[illegible]	[illegible]		[illegible]																						[illegible]			[illegible]
[illegible]	1911	[illegible]						2	3	17	13	16	13	**12**	11	[illegible]	1																							[illegible]	[illegible]
[illegible]	[illegible]	[illegible]						2	2	13	12	14	**17**	12	[illegible]	[illegible]																						[illegible]			[illegible]
[illegible]	[illegible]	[illegible]						1			[illegible]	[illegible]	16	[illegible]	9	[illegible]																						[illegible]			[illegible]
[illegible]	[illegible]	[illegible]							6	10	6	22	[illegible]	**14**	[illegible]	4																						[illegible]			[illegible]
[illegible]	[illegible]	[illegible]								4	6	14	20	26	9	[illegible]		1																				[illegible]			[illegible]
[illegible]	[illegible]	[illegible]									1	[illegible]	[illegible]	[illegible]	24	[illegible]																						[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]							1		3	1	[illegible]	[illegible]	7	17																						[illegible]		[illegible]	
[illegible]	[illegible]	[illegible]									1		[illegible]	[illegible]	17	19	11	[illegible]	[illegible]																					[illegible]	[illegible]
[illegible]	[illegible]	[illegible]											20	[illegible]	29	[illegible]	[illegible]	1	2																						
1149	1911	F3									1		2	[illegible]	24	[illegible]	[illegible]																					[illegible]			

* Duplicates.

Broken lines indicate ranges for ripening and solid lines approximate ranges for flowering.

Black-faced type indicates parent class.

Italics refer to exposure of silk, other figures to shedding of pollen.

no genetic correlation between time of maturity of the two sorts of flowers, crossing any very early with any very late variety of corn, both of which are protandrous, must result always in F_2 plants more strongly protogynous than any now known and also some plants more decidedly protandrous than any known.

SUMMARY AND GENERAL CONCLUSIONS.

The object of this paper, as stated in the introduction, is to discuss somewhat fully the inheritance of quantitative characters and to present data bearing upon this subject secured from experiments with maize. The results of these experiments, given in detail earlier in this paper, are here summarized.

The inheritance of number of rows per ear has been studied in eight different crosses. The parent varieties were of 8-rowed, 12-rowed, 16-rowed, and 20-rowed types. In nearly every case F_1 was intermediate between the parents, tho in case of one cross of an 8-rowed variety with an apparently 12-rowed variety, the latter condition seemed to be dominant. In most cases the F_2 generations had a wider range of variation than F_1, a range that included both parent types. Differences between the F_2 families of a single cross are believed to have been due to heterozygosis of one or other of the parent varieties. Where F_3 families were grown, the parent types were recovered in every case and intermediate types were also seen. In one case a series of F_3 lots, from a single cross, showed modal conditions of 12, 14, 16, 18, and 20 rows.

Inheritance of length of ears was studied in three crosses of distinct varieties. In each case the ear length of one parent was approximately two and one-half times that of the other parent. In the cross of Tom Thumb with Black Mexican, the F_1 ear length was distinctly intermediate between the parental ear lengths. In the cross of Missouri dent with California pop, on the other hand, the F_1 generation had ears practically as long as those of the long-eared parent, but here the extreme length of the F_1 ears was doubtless in part due to heterozygosis, for the means of the F_2 families were distinctly intermediate between the parental means. In every case the F_2 fraternities were more variable than the F_1 lots. In most cases the F_2's completely bridged the gap between the parents and in one case the F_2 range of variation was from practically the shortest ears of the short-eared parent to beyond the longest ears of the long-eared parent. The short-eared parent type has not as yet been recovered in any F_3 lot and in only a few F_3 families has the ear length been equal to that of the long-eared parent. In case of each cross, however, the ears of some F_3 families averaged nearly twice as long as the ears of other F_3

families. Nor was this difference in size the only feature differentiating the several F_3 families. The variability of some F_3 lots was no greater than that of the parents or of F_1, while other F_3 lots equaled in variability the F_2 generation.

Inheritance of diameter of ears was investigated in two crosses. The ears of F_1 were intermediate in diameter between those of the parents, but somewhat nearer the large-eared than the small-eared variety. The F_2 ranges of variation little more than filled the gap between the parent races. The parent types were not recovered in F_3, but the several F_3 lots were very distinct. The smallest ears of the largest eared F_3 families were larger than the largest ears of the smallest-eared family.

Weight of seeds was determined only for the cross Tom Thumb × Black Mexican. The seeds taken to represent the latter variety were probably too large, owing to previous mixture of strains. If allowance is made for this, the F_1 seed weight was only a little below the mid-parental weight and the ranges of variation of the F_2 fraternities well overlapped the ranges of the parents. Tho distinct types of seed weight were isolated in F_3 neither parent type was recovered. One F_3 family, however, had a seed weight nearly equal to that of Black Mexican and the great variability of several F_3 lots indicated heterozygosity sufficient to enable the isolation of the parent types on further selection.

Breadth of seeds was noted in the crosses of Missouri dent with California pop and with Tom Thumb. In both cases F_1 was distinctly intermediate between the parents in breadth of seeds. The variability of the F_1 lots was not noticeably greater than that of the parents. The F_2 generation, on the contrary, showed a markedly greater variability than F_1 or the parents. In one cross the combined range of variation of all the F_2 families together was not sufficient to overlap even the inner extremes of the parents, but in the other cross, while the F_2 ranges were not greater, the parents differed less in seed size, so that practically all the classes from below the mean of the small-seeded parent to above the mean of the large-seeded parent were occupied by F_2 individuals. Two of the F_3 lots of the latter cross, grown from small-seeded F_2 individuals, had seeds practically as small as those of the small-seeded parent. Since the total number of F_2 plants was slightly over 300 in each cross, it is thought that Missouri dent and Tom Thumb pop probably differed by not over five factors and Missouri dent and California pop by perhaps as many as six factors influencing breadth of seeds.

Four different crosses were employed in the studies of the inheritance of height of plants. A peculiarity of these crosses is that in three of them the F_1 plants were almost as tall as the tall parent and in the fourth were considerably taller than the mean of the two parents. That this increase in height of F_1 plants over the mid-parental height is in no case ascribable to dominance of tallness over shortness, but is due rather to increased vigor accompanying heterozygosis, is indicated by the fact that in every case the mean height of the F_2 plants is about half-way between the heights of the parents and is also shown by the lack of skewness in the F_2 frequency distributions. Practically all of the F_2 fraternities overlapped in height the inner extremes of their parents. Most of them had a range of from near the mean height of one parent to the mean height of the other parent and in one cross the F_2 range was from the minus extreme of the short parent to the plus extreme of the tall parent. The F_3 families were very diverse in height and in variability. Few F_3 families were as tall as the tall parent and none was quite so short as the short parent, tho the latter was approached very closely in a few cases. In case of some of the extreme F_3 lots, the variability was sufficient to make it probable that types like the parents could be isolated in the next generation. Moreover, certain F_3 families with heights variously intermediate between the parents had variabilities small enough to indicate the possibility of their breeding true to these heights.

In some of these crosses, the height of plants was separated into its components—number of nodes and internode length. In number of nodes the F_1 families were strictly intermediate between the parent varieties and the mean number of nodes in F_2 was practically the same as in F_1, both of which facts indicate that number of nodes is not appreciably affected by heterozygosis. As in all the other quantitative characters studied, the F_2 generation exhibited a wide range of variation and the several F_3 families had very different mean numbers of nodes, including types approaching those of the parents and also various intermediate types.

A study of internode lengths explains the excess in height of F_1 plants over the average of the parent heights. Tho number of nodes in F_1 is apparently always distinctly intermediate between the parent numbers, the internode length is so greatly increased by heterozygosis that F_1 plants are often nearly as tall as the tall parent, and always taller than the average of the parent heights—the former when the tall and short parents differ little and the latter when they differ much in number of nodes. In the two crosses in which internode length was calculated, the F_1 plants had internodes longer than those of the long-internode parent. In Tom Thumb × Missouri dent, in fact, the latter variety had an internode length almost exactly half way between that of the other parent variety and of the F_1 generation. One of the F_2 families of this cross had a range of variation extending from considerably below the minus extreme of the short-internode parent to much above the plus extreme of the long-internode parent and even considerably above the plus extreme of F_1. This extreme range in F_2 is thought to be due to new combinations of the internode-length factors of the two parents.

In two crosses, one parent of which produced numerous tillers and the other few tillers, F_1 was intermediate in number of stalks per plant. In both crosses F_2 was more variable than F_1 and in one cross the F_2 range was from one to eight stalks, while five was the largest number observed in the parent variety that tillered most freely. Among the F_3 families, a few were practically one-stalked types and a few others had a somewhat larger mean number of stalks than the tillering parent and a range of variation so great as to suggest the possibility of isolating by selection a type with a still larger number of stalks.

On account of the fact that in one cross the tall parent was a few-stalked type and the short parent a many-stalked type, the two parent varieties did not differ greatly in total length of stalks per plant. Owing to the intermediate number of stalks in F_1 and to the tallness of F_1 stalks in this cross, the total length of stalks in F_1 was much greater than that of either parent—in fact almost equal to the combined stalk lengths of the parents. The mean total length of stalks of F_2 was much less than of F_1 but the variability was considerably greater. In another cross, where the parents differed much more in total length of stalk, no records of the F_1 generation are available, but the mean total stalk length in F_2 (which was doubtless less than in F_1) was somewhat greater than that of either parent. Owing apparently to a lack of correlation—either physiological or genetic—between number of stalks and height of plant, some of the F_3 lots of this cross had a mean total length of stalk twice as great as that of the long-stalked parent and one F_3 family had a mean length greater than the plus extreme of that parent. This great stalk-length is thought to be due in the main to a combination of the factors influencing total stalk length, some of which come from one parent and some from the other.

In earliness F_1 plants were intermediate between their parents. The F_2 generation more than filled in the gap between the parents in all cases where exact records were made and in one case had a range from below the mean of the early parent to above the mean of the late parent. Very distinct types were obtained in F_3, some of which were practically as early in flowering as the early parent but none of which were quite so late as the late-flowering parent. In general the same relative order was maintained in ripening as in flowering. Roughly the number of days from planting to flowering was 60 per cent of the number of days from planting to ripening. The relative lengths of the two periods may, however, depend somewhat upon the season at which the type in question matures.

In general, then, it may be said that the results secured in the experiments with maize were what might well be expected if quantitative differences were due to numerous factors inherited in a strictly Mendelian manner. It is quite likely, as pointed out repeatedly in the detailed discussion of results, that genetic correlations occur between factors for distinct quantitative characters. These and the physiological correlations so frequently noted make the results more difficult of interpretation, but do not throw them out of the realm of Mendelian phenomena. Physiological correlation is a phenomenon of development, not of inheritance, and, as such, has less interest for students of genetics than for experimental morphologists. Even in practical plant breeding, correlations of this sort are of importance mainly on account of the physiological or morphological limits that they set to the perfect development of particular combinations of characters.

Real genetic correlations in the sense of gametic associations, are not antagonistic to the Mendelian doctrine. True, the fundamental principle of Mendelism is segregation of separate factors and it might, therefore, be held with some degree of plausibility that gametic coupling of factors is non-Mendelian. But where the associated factors segregate regularly from other factors or other groups of factors, they can certainly be said to Mendelize —they merely Mendalize together. Such correlations as these have distinct importance in genetics.

Numerous apparent correlations, genetic as well as physiological, have been encountered in these experiments and many of them have been noted incidentally in the detailed discussions of results. We have reason to believe, for instance, that length of ear is directly correlated with height of plant and inversely correlated with number of rows per ear. Number of rows seems also to be related in some way to the character of the endosperm, since in some crosses segregates with a large number of rows have dent grains while those with few rows have flinty grains. It is apparent also that, while height of plant and number of stalks per plant may not be directly related, number of stalks and diameter of stalks are negatively correlated. Our records indicate that there is little if any correlation, either genetic or physiological, between duration of growth and internode length. There is also little or no physiological correlation between duration of growth and number of nodes, but apparently a distinct genetic correlation between these two characters. In 1911, families of corn, which from previous selfing were approaching a condition of homozygosis of factors for size and duration of growth, showed a slight negative correlation between number of nodes and duration of growth, while F_2 families, heterozygous for both number of nodes and for duration of growth, showed a marked positive correlation between these characters. If height of stalk alone had been considered instead of number of nodes and internode length, it might have been thought, in case of these F_2 families, that the unfavorable weather of early summer, by checking the growth of the early plants, and the favorable weather of late summer, by increasing the growth of the late plants, had brought about an apparent rather than a real correlation. But since the number of nodes is determined before the plant has made much growth, this character could not have been influenced by the differences between the weather of early and that of late summer. It is not that one set of conditions made the early plants have few nodes and another set made the late plants have many nodes, but rather that some of the genetic factors that caused the plants to have a large number of nodes were associated with the factors (or were themselves the factors) that caused prolonged growth. It is expected that the detailed evidence upon which this conclusion is based will be prepared for publication in the near future.

The interrelations of such characters as number of rows per ear, circumference of ear, and breadth of seeds are obvious. An ear, of course, could not have many rows and a small circumference without having very narrow seeds. But this and similar relations are in the main mere mechanical adjustments rather than physiological—to say nothing of genetic—correlations.

It is often impossible to tell in a particular case whether distinct factors are coupled in inheritance or whether a single factor plays a part in the development of what are regarded as distinct characters. In the latter case the problem is fundamentally one of the physiology of development rather than of genetics.

Certain quantitative relations in maize illustrate the influence of a single factor in the development of two or more characters as well as the influence of several factors in the development of a single character. It is obvious that any factor that affects say internode length will also have an influence upon length of stalk and therefore, in addition, upon stalk weight and even upon total weight of plant. Likewise any factors influencing number of nodes, any with an effect upon amount of tillering, any factor for diameter of stalk, size of ears, number of ears, etc., will all be concerned in the development of the one character complex—total weight of plant. If one argue that total weight is not a simple character, he must also admit that neither is length of stalk, which of course is determined by the number of nodes and the internode length, and must not forget that even the length of one internode is the product of the number and the length of the cells contained in it. Tho total weight can thus be analyzed into numerous sub-characters, it is none the less a "character" of the plant or type in question.

It was shown earlier in this paper that the multiple-factor hypothesis furnishes a satisfactory and simple interpretation not only of all of the results secured from these maize experiments but also of the results from experiments previously reported for other plants and for animals. We are familiar with no hypothesis not based upon the Mendelian principle of segregation and recombination of factors which furnishes a plausible explanation of many of the facts regarding the inheritance of quantitative characters. We are aware of the suggestion (Castle 1912) that a heterogeneous distribution of growth-inducing substances in the cells of an organism would result in variability in its progeny, that this heterogeneity of the protoplasm would be increased by crossing, and that, therefore, the variability would be increased in generations beyond F_1. This hypothesis cannot, however, be said to interpret satisfactorily the facts of size inheritance, until it is shown, for instance, how one F_2 plant of a size intermediate between the parent varieties can produce an F_3 progeny of great variability while another F_2 plant of the same intermediate size yields an F_3 progeny scarcely more variable than the parents or the F_1 generation. In other words, it must first be shown how some F_2 plants come to have the size of F_1 plants and at the same time have the comparatively homogeneous distribution of growth-inducing substances characteristic of the parent races while other F_2 plants are like F_1 plants in both size and heterogeneity of these substances. And even if increased protoplasmic heterogeneity of general growth-inducing substances can be made to account for the increased variability ordinarily observed in F_2, it is still not quite clear just how such a condition can bring about an F_2 range of variation away beyond the outer extremes of the parents in respect to one size character, while the range of variation of some other size character of the same F_2 individuals is scarcely enough to bridge the gap between the inner extremes of the parents.

THE MANIPULATION OF QUANTITATIVE CHARACTERS IN PLANT BREEDING.

The principal use of hybridization in plant breeding is to secure new combinations of the characters present in the parents—to combine in one race the desirable characters of the parent races and to eliminate the undesirable characters. In some cases a condition intermediate between the parents with respect to a certain character may be desired. Crossing may also be of value for bringing out characters that were latent in the parents, tho, since such possibilities are usually unforeseen, this is seldom the main object of any cross. The increased vigor induced by heterozygosis, tho often of value in plant breeding, is aside from the purpose of this discussion.

The method of procedure to be followed in combining the more simple independent Mendelian characters is well known. All that is necessary to do is to cross appropriate types and to grow a sufficient number of F_2 individuals to be sure of getting the desired combination of characters in the homozygous condition. When this has been done it remains merely to propagate the new types. If it is known beforehand upon what factors the desired characters depend, it can even be told how many F_2 individuals must be grown to afford an even chance of getting the combinations wanted. For instance, if it were desired to combine in one variety of corn the two characters sugary endosperm and a peculiar, erect leaf-habit, due to the absence of auricles from the base of the leaves (Emerson 1912), a type that was first found in cultures of dent corn, and if all the other characters of this non-auriculate dent corn were sufficiently like those of the sweet corn chosen as the other parent so that they could be disregarded, or if it were immaterial what these other characters were, then the two varieties could be crossed with considerable assurance that about one in every sixteen F_2 plants would be homozygous for both erect leaves and sugary endosperm. Or better yet, since segregation in endosperm characters occurs on F_1 ears, only sugary grains need be planted, with the assurance that all the progeny will be sweet corn and about one in four will have erect, non-auriculate leaves.

The procedure when dealing with quantitative characters differs in no way from that outlined above, except that, since more factors are concerned, more individuals must be grown in F_2 or else the F_3 and perhaps even the F_4 generation must be awaited for the desired combination. As a matter of fact even the more simple qualitative characters are rarely ever so easily handled in actual practice as is indicated by the example given above. It almost never happens that both of the types chosen for crossing are alike in all but one or two characters. A breeder does not usually want merely to combine one desirable character of a certain variety with one other equally desirable character of another variety. He perhaps has a variety that for certain uses is almost ideal but it lacks conspicuously some one or two very desirable characters that he sees in some other variety. He wants to keep his variety as it is but transfer bodily to it the coveted character from the other variety. Very likely this second variety is only mediocre in numerous respects. As a matter of fact, the two varieties, instead of differing by merely this one prominent character, actually differ in very many characters. In transferring, therefore, the much desired character to the otherwise ideal variety, one is apt to lose some of the highly-prized characters of the latter, unless very large numbers are grown in F_2 or selection practiced for two or three more generations. The only difference in manipulation between quantitative and qualitative characters is, then, one of degree. And in practical breeding even this distinction is of little importance, since practically every cross between commercial varieties must necessarily include both qualitative and quantitative characters.

The large number of factors by which distinct commercial sorts of crop plants are differentiated is almost staggering. Take as an illustration an extremely simple case. We will suppose that it is desired to produce a better silage corn than that afforded by the tall few-stalked dent varieties of the West and South or the short many-stalked flint varieties of the Northeast—in short a type of corn combining the tallness of one variety with the many-stalked condition of the other. For sake of simplicity, we will disregard differences in season of ripening and various other characters, which, as a matter of fact, could not ordinarily be disregarded in actual practice. We will assume that the varieties in question differ by five Mendelian factors influencing height of plant and by five factors affecting number of stalks per plant and that each of these factors is independent of the others in inheritance—assumptions which, tho they may not represent accurately the actual facts, are at least not unreasonable and will at any rate serve for purpose of illustration. From a cross of these varieties, an F_2 of only about 1,000 plants, or say one-tenth acre, would be required to give an even chance of recovering a many-stalked type like the one parent or a tall-stalked type like the other parent. Perhaps three or four times that many plants should be grown to be at all sure of recovering the parent types. But with this number of individuals there could be no hope that any of the very tall plants would also have very many stalks. With the parents differing by ten factors, five for height and five for number of stalks, as was assumed, over a million F_2 plants, or in other words over one hundred acres, would be required for an even chance of getting the desired combination of characters, and at least two or three times that number should be grown to make sure of results. Now, while perhaps breeding work on such a scale is not impossible, it is certainly out of the question under ordinary conditions. What method then can be used in such cases? Or are the proposed results impossible of accomplishment?

Under the conditions assumed here, the method of back crossing with one parent type (Castle 1911), cannot be used, for, while insuring the ultimate recovery of say the many-stalked parent type, it would at the same time make impossible the recovery of the tall-stalked type of the other parent. The only method available in such cases is to grow as many F_2 plants as is practicable, select such plants as combine most nearly the desired combination of height and number of stalks, and from selfed seed of these grow F_3 progenies, from which in turn further selections must be made, and so on for as many generations as are necessary. In this way, results can be secured with a much smaller total number of plants but of course at the expense of considerably more time.

It may not be out of place here to show more definitely just how the element of time can be made to take the place of numbers in solving a breeding problem like that discussed above. For sake of simplicity, let us now assume that the parents differ in only four factors for height and four for number of stalks, eight in all, thus requiring something over 65,000 F_2 plants for an even chance of getting the desired combination of many stalks and tall stalks. By referring back to Table 1 (page 19), we can see at a glance what behavior will result both in F_2 and in F_3 following a cross the parents of which differ in four factors *A*, *B*, *C*, *D*. If the class headings are read as decimeters, they will represent well actual heights of short and tall corn plants. Each single factor will then be assumed to add two decimeters to the initial height of 10 decimeters. If now we call the factors *A′*, *B′*, *C′*, *D′* and suppose each to add one stalk to an initial 1-stalked condition, the same table will serve to illustrate the inheritance of number of stalks per plant where the parents are 1-stalked and 9-stalked respectively. Now from the cross of a 1-stalked, 26-decimeter type with a 9-stalked, 10-decimeter type, we see from Table 1 that, out of 256 F_2 individuals, one should have the formula *AABBCCDD* and also that one should have the formula *A′A′B′B′C′C′D′D′*. In other words, there should be one 26-decimeter plant and also one 9-stalked plant. But the 26-decimeter plant would almost surely not have 9 stalks and the 9-stalked plant would not be 26 decimeters tall, unless about 65,000 F_2 plants, instead of 256, were grown. To be sure of getting one 9-stalked plant, let us grow four times the number indicated in Table 1, or approximately 1,000 F_2 plants. Since over 70 per cent of all the F_2 plants are from 16 to 20 decimeters tall, the chances are that the one 9-stalked plant will be from 16 to 20 centimeters tall—if taller so much the better. Let us suppose that it is 18 decimeters tall like the F_1 plants.

On selfing this one 9-stalked, 18-decimeter plant, what will be obtained in F_2? We can be sure that the progeny will all be of the 9-stalked type. Table 1 shows that out of the 70 18-decimeter plants, 6 (group III) will breed true, 48 (group XI) will have an F_3 range from 14 to 22 decimeters, and 16 (group XV) will have an F_3 range from 10 to 26 decimeters. If then the 9-stalked F_2 plant belonged in group XV for height, we would have an even chance of getting one 9-stalked, 26-decimeter plant by growing only 256 F_3 individuals and would be fairly sure of getting it by growing 1,000 F_3 plants. In short, we would accomplish with 2,000 F_2 and F_3 plants what we would have had only an even chance of accomplishing with 65,000 F_2 plants or what would have required perhaps 250,000 F_2 plants to make its accomplishment fairly sure. If, however, as is much more likely, the 9-stalked, 18-decimeter F_2 plant belonged in group XI in height, its F_3 progeny, while breeding true to the 9-stalked condition, would have a range from 14 to 22 decimeters. Since all the individuals of group XI are heterozygous in only two factors, an F_3 generation of 16 plants would afford an even chance—and 50 plants make fairly sure—of getting one 9-stalked, 22-decimeter plant. But also, since all the F_2 individuals of group XI lack one of the four height factors, the one 22-decimeter F_3 plant must be homozygous for three factors and lack the fourth, like the F_2 plants of group IV, and will, therefore, breed true to this height. There will then be no possibility of producing a 26-decimeter type from it directly any more than from an F_2 18-decimeter plant belonging to group III, which would of course breed true to that height. Crossing between different F_3 types must then be resorted to.

We have assumed that a 9-stalked, 22-decimeter plant has been produced as described above by selection from 1,000 F_2 and 50 F_3 plants. From the same 1,000 F_2 plants a 26-decimeter, 5-stalked plant could also have been selected and would of course have bred true to the 26-decimeter height. It would possibly also have bred true to the 5-stalked condition (if belonging to group III for number of stalks), or possibly would have produced an F_3 range from 1 to 9 stalks (if belonging to group XV for stalk number), in which case the desired 26-decimeter, 9-stalked type would have been secured in F_3. But since the chance is greater, let us suppose that the 26-decimeter, 5-stalked F_2 plant belonged to group XI for number of stalks. Then by growing 50 F_3 plants from it, we would be fairly certain of getting at least one 26-decimeter, 7-stalked plant which would breed true in both height and number of stalks. The next step, obviously, is to cross this homozygous 26-decimeter, 7-stalked F_3 plant, or any of its F_4 progeny, with the 9-stalked, 22-decimeter F_3 plant obtained from the other selection, or with any of its F_4 progeny. The two F_3 plants would have zygotic formula similar to the following:

(1) 26-decimeter, 7-stalked plant—$AABBCCDD$—$A'A'B'B'C'C'd'd'$.

(2) 22-decimeter, 9-stalked plant—$AABBCCdd$—$A'A'B'B'C'C'D'D'$.

It is clear, therefore, that since the two F_3 plants, (1) and (2), differ only in the factors D and D', only 16 F_4 plants—or say 50 to make more sure—need be grown to give one plant that is homozygous in all eight factors. We have then grown 1,000 F_2 plants, 100 F_3 plants, and 50 F_4 plants to accomplish what would perhaps have required a quarter-million F_2 plants alone. And it would have taken no more plants and no more time had we crossed the 9-stalked, 22-decimeter F_2 plant with the 7-stalked 26-decimeter one instead of having first grown their F_3 progenies.

In the same way it can be shown that the desired combination of quantitative characters could be secured in comparatively few generations even if a sufficient number of plants could not be grown in F_2 to recover the exact parent type of either character in any individual. But the theoretical possibilities have been sufficiently illustrated.

In the detailed account of our experiments, several examples have been pointed out that illustrate the possibility of securing parent types in F_3 from F_2 lots that contained no individuals as extreme as the parents. For instance, in certain crosses, no F_2 plants had seeds quite like those of the parent varieties, but in F_3 the parent sizes were recovered in several cases. (See Tables 20, 22, 24.) Perhaps the most striking case of this sort observed in our experiments is that of height of stalk. While in some crosses the parent heights were recovered in F_2, in other crosses the most extreme F_2 heights lacked much of reaching the outer extremes of the parent ranges. In Tom Thumb × Black Mexican (Table 25), this was true of the F_2 families, but two of the F_3 lots—progenies of approximately the smallest F_2 plants—

contained individuals very near the minus extreme of the small parent.

In actual practice, of course, one must use larger numbers than those declared, a few paragraphs back, to be sufficient. Following one assumption, it was shown that 1,000 F_2 and 1.000 F_3 plants—2,000 in all—would be as likely to give the desired results as about 250,000 F_2 plants, while following another assumption, it was seen that 1,000 F_2, 100 F_3, and 50 F_4 plants—only 1,150 in all—would be required to secure the same result. And the assumptions in these two cases were that the F_2 plants selected differed not in size but merely in zygotic formulae. Since in practice, however, there is no way of distinguishing between the several F_2 plants all belonging to the same size class but having different zygotic formulae, as many F_3 individuals will of course have to be grown from the F_2 plant that is heterozygous in only two factors as from the one that is heterozygous in four factors. Furthermore—and even more important than this—it cannot be known whether two plants of the same size actually belong in the same size class. Not only may plants that belong in the same size class have different zygotic formulae, but those that belong in very different classes may be forced together and made to appear to belong in the same class by the specially favorable conditions surrounding one and the unfavorable conditions surrounding another, or those not only belonging in the same class but having identical zygotic formulae may similarly be made to appear in different classes.

Numerous examples of confusion of this sort arising thru our inability to distinguish at sight between genetic variations and mere fluctuations have been encountered in our experiments. One will be sufficient for illustration. Of all the F_3 families in one cross (Table 36), No. 1146 had the largest number of stalks per plant, its mean being 4.24 stalks, but its F_2 parent had only three stalks—less than the mean of the F_2 family (510) to which it belonged. F_3 family 1149, on the other hand, had a mean number of stalks of only 2.04 notwithstanding that its F_2 parent had four stalks—above the F_2 mean. One of these F_2 plants had been forced below and the other above its true class. In height of plant (Table 29), family 1149 exceeded family 1146 by only 2.37 decimeters, their respective mean heights being 25.14 and 22.77 decimeters, tho the F_2 parents of 1149 belonged to the highest F_2 class and was about four decimeters taller than the F_2 parent of 1146. If one had been selecting a single F_2 plant for both height and number of stalks, the 23-decimeter, 4-stalked parent of 1149 would doubtless have been chosen in preference to the 19-decimeter, 3-stalked parent of 1146, but 1149 actually had a mean total stalk length of only 40.29 decimeters while that of 1146 was 79.88 decimeters—almost twice as great. Evidently in actual practice one must select a number of promising F_2 plants to stand a fair chance of getting an F_3 type to his liking.

There is very little doubt that the striking results secured in the well known selection experiments with corn carried out at the Illinois Experiment Station (Smith 1908) are to be explained on the same basis as that used in this discussion to show how types can be isolated by the proper use of small numbers of plants in F_2, F_3, F_4, or later generations—types that could not be expected to appear in F_2 unless excessively large numbers were grown. If oil and protein content in corn are inherited in the same way that other quantitative characters are, we should not expect to find very high or very low oil or protein content in any 100 or 200 ears taken at random from a lot of open-pollinated, unselected plants, most of which are almost certainly heterozygous in oil and protein factors—just as they are known to be for other characters—and have, therefore, an intermediate development of these characters. It is not necessary to resort to the somewhat mystic idea that selection (the mere act of choosing) has profoundly changed the oil and protein characters of this corn nor to call into service the possibility that mutations occurred repeatedly during the progress of the experiment. There is as much reason for assuming that the height-of-plant character as exhibited in the F_2 ranges (Table 25) was changed into a much smaller height character in F_3 by selection or that a mutation occurred opportunely. Between the isolation of a short-stalked type in F_3 from a largely heterozygous F_2 and the isolation of a low or high oil type from an open-fertilized lot of corn—also largely heterozygous—there is apparently no foundamental difference.

A word should be said of the practical possibilities of producing sizes greater or less than the parent sizes. A noticeable example of this from our own experiments is the production of a type with a total length of stalks more than twice that of the larger parent. (See Table 38.) This was accomplished by combining the many-stalked condition of one parent with the tall-stalked condition of the other parent. Visibly different parent characters were combined to form a new character complex. The production of a type with internodes much longer than those of the parents (Table 33) differs from the above only in that here the parent types were apparently very similar and it could not be foreseen that the similar internode lengths of the two varieties were due to different factors that could be combined into a new character complex by crossing. It is of course unlikely that many crosses between varieties having similar quantitative characters will be made with the avowed object of securing combinations of factors unlike the combinations responsible for the parent characters, but the idea is well worth keeping in mind. When the factors that have to do with the development of the principal crop plants have all been sorted out and tagged—as they will be some day—breeders can proceed in their undertakings with much more assurance than at present.

By way of summary it can be said that a breeder dealing with quantitative characters should proceed just as he would if dealing with such qualitative characters as color where the parent types differ in respect to numerous characters. The principal differences between the two cases are that quantitative crosses are likely to differ in more factors than qualitative ones and that environmental influences cause more confusion. He should in short grow as many F_2 plants as his facilities allow. From these he should select *numerous* promising individuals, self pollinate them and grow their progenies on as large a scale as practicable. If any of these F_3 lots are of the desired type he will of course propagate them and discard the others, or if not he can at least discard some of them and continue his selection from the most promising ones. Or if no F_3 family shows by its range of variation any tendency to produce ultimately a type better than itself, resort should be had to intercrossing between the several more promising F_3 lots or between their F_4 progenies, with the hope (we might almost say assurance) that among these several types, tho they are similar in appearance, there exist sufficiently different sets of factors to insure the desired combination in crossing. When dealing with plants like corn that are much more vigorous when many characters are heterozygous, the breeder will find it necessary to practice cross breeding between different isolated types or to provide for natural crossing. He should not, therefore, be content with the production of a single strain of the desired type—say a single high-oil type—but should isolate two or more such types, both of which are high in oil content, but which differ by enough minor characters, quantitative or qualitative, to insure a vigorous development on crossing them or on allowing them to intercross naturally when grown in mixtures.

These methods apply just as well to improvement by selection from the complex hybrid mixtures, which, because of some outstanding features, have been assigned varietal names, as they do to the isolation of types from the similar, tho perhaps somewhat more complex, hybrid mixtures resulting from the crossing of two named varieties. The difference at most is only a matter of degree. The breeder who selects for high-oil content from open-pollinated plants will, if he persists long enough, succeed in producing a type with enough factors for oil production to rank as a high-oil type and with these factors sufficiently homozygous to insure comparative constancy, while at the same time a sufficient number of factors for other minor characters are heterozygous to insure a comparatively vigorous strain. But by self-pollination, together with the same sort of selection, several practically homozygous high-oil strains could almost surely have been produced in much less time. And these strains would doubtless have been sufficiently unlike in factors for minor characters to insure abundant vigor of growth on crossing them. While a few years' time may not be an important consideration where the character in question can be determined at sight or by mere weighing or measuring, in breeding work requiring costly chemical analysis it is extremely important that the desired results be obtained in as few years and therefore with as few analyses as possible.

LITERATURE CITED.

BELLING, JOHN

Second generation of the cross between velvet and Lyon Beans. Ann. Rpt. Florida Agr. Exp. Sta. **1911**: 82-103. 1912.

CASTLE, W. E., ET AL.

Studies of inheritance in rabbits. Carnegie Inst. of Washington. Pub. **114**: 1-70. 1909.

Heredity in relation to evolution and animal breeding. New York. Appleton, pp. 1-184. 1911.

The inconstancy of unit characters. Amer. Nat. **46**: 352-362. 1912.

EAST, E. M.

The distinction between development and heredity. Amer. Nat. **43**: 173-181. 1909.

A Mendelian interpretation of variation that is apparently continuous. Amer. Nat. **44**: 65-82. 1910.

The Genotype hypothesis and hybridization. Amer. Nat. **45**: 160-174. 1911.

EAST, E. M., and HAYES, H. K.

Inheritance in Maize. Bul. Connecticut Agr. Exp. Sta. **167**: 1-141 Pl. 25. 1911.

EMERSON, R. A.

Inheritance of sizes and shapes in plants. A preliminary note. Amer. Nat. **44**: 739-746. 1910.

Latent colors in corn. Ann. Rpt. Amer. Breeders' Asso. **6**: 233-237. 1911.

Genetic correlation and spurious allelomorphism in maize. Ann. Rpt. Nebraska Agr. Exp. Sta. **24**: 60-90. 1911a.

The inheritance of the ligule and auricles of corn leaves. Ann. Rpt. Nebraska Agr. Exp. Sta. **25**: 81-88. 1912.

HAYES, H. K.

Correlation and inheritance in *Nicotiana tabacum*. Bul. Connecticut Agr. Exp. Sta. **171**: 3-45. Pl. 5. 1912.

LANG, A.

Die Erblichkeitsverhältnisse der Ohrenlänge der Kaninchen nach Castle und das Problem der intermediären Vererbung und Bildung konstanter Bastardrassen. Zeitschr. f. induktive Abstammungs- und Vererbungslehre **4**: 1-23. 1911.

MILLARDET, A.

Note sur l'hybridation sans croisement ou fausse hybridation. Mém. Sec. des Sci. phys. et nat. de Bordeaux **4**: 4me Série. 1894.

NILSSON-EHLE, H.

Einige Ergebnisse von Kreuzungen bei Hafer und Weizen Botan. Notiser **1908**: 257-294. 1908.

Kreuzungsuntersuchungen an Hafer und Weizen. Lunds Universitets Arsskrift, n. s. sec. 2, vol. 5, no. 2, pp. 1-122. 1909.

Kreuzungsuntersuchungen an Hafer und Weizen II. Lunds Universitets Arsskrift, n. s. sec. 2, vol. 7. no. 6, pp. 1-82. 1911.

PHILLIPS, JOHN C.

Size inheritance in ducks. Jour. Exp. Zool. **12**: 369-380. 1912.

SHULL, G. H.

Hybridization methods in corn breeding. Amer. Breeders' Mag. **1**: 98-107. 1910.

SMITH, LOUIE H.

Ten generations of corn breeding. Bul. Illinois Agr. Exp. Sta. **128**: 453-575. 1908.

TAMMES, T.

Das Verhalten fluktuierend variierender Merkmale bei der Bastardierung. Recueil des Travaux Botaniques Neerlandais **8**: 201-288. 1911.

VON TSCHERMAK, E.

Über die gesetzmaszige Gestaltungsweise des Mischlinge. Zeitschr. f. d. Versuchswesen in Oesterreich **1902**: 781-861. 1902.

Weitere Kreuzungsstudien an Erbsen, Levkojen und Bohnen. Zeitschr. f. d. Versuchswesen in Oesterreich **1904**: 533-638. 1904.

Über die Vererbung der Blütezeit bei Erbsen. Verhandl. d. naturforsch. Vereines in Brünn **49**: 1-23. 1912.

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BY F. J. ALWAY.

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CONTENTS.

PAGE

Introduction 5

Review of previous work—
  Older view of the importance of the hygroscopicity of soils 8
  Recognition of the falsity of the older view 10
  Studies of the hygroscopic coefficient by Hilgard and Loughridge .. 12
  Later studies on the nonavailable water and on the relative hygroscopicity of soils 14
  Previous studies by the writer 16
  Recent studies by Briggs and Shantz 18

General description of the experiments 21
  Soils used 21
  Plants grown 21
  Greenhouse used 21
  Determination of the soil moisture 28
  Free water 30
  Wilting coefficient 31
  Determination of the dry matter of the crops 32

Preliminary experiment 32

Growth of wheat on semi-arid soil compared with that on humid soil. Experiment of 1909 33
  Summary of experiment 44

Growth of crop plants with different amounts of water in the subsoil. Experiment of 1910 45
  Filling the cylinders 48
  Separation of roots from the subsoil 49
  Cylinders without plants 51
  Red Fife wheat 52
    Cylinder with no free water in the subsoil 58
    Cylinders with 4 per cent free water in the subsoil 60
    Cylinder with 7 per cent free water in the subsoil 61
    Cylinder with 12 per cent free water in the subsoil 61
    Two cylinders with moister soil near the surface 61
  Kubanka wheat 62
    Cylinder with no free water in the subsoil 65
    Cylinder with 4 per cent free water in the subsoil 65
    Cylinder with 8 per cent free water in the subsoil 65
    Cylinder with 12 per cent free water in the subsoil 67
    Two cylinders with moister soil near the surface 68
  Milo 68
    Cylinder with no free water in the subsoil 69
    Cylinder with 4 per cent free water in the subsoil 69
    Cylinder with 8 per cent free water in the subsoil 69
    Cylinder with 12 per cent free water in the subsoil 70
    Two cylinders with moister soil near the surface 71
    Mexican beans 74
  Summary of experiment of 1910 76

PAGE
Experiment with loess soils from different parts of the Transition region. Experiment of 1911 78
  Red Fife wheat 83
  Milo 90
  Mexican beans 99
  Maize 104
  Summary of experiment of 1911 106
Experiments with perennial desert legumes 108
  Experiment 1 108
  Experiment 2 110
  Experiment 3 111
  Summary of experiments 114
The hygroscopic coefficient versus the wilting coefficient in comparisons of the available moisture of soils 115
Summary and conclusions 119

STUDIES ON THE RELATION OF THE NON-AVAILABLE WATER OF THE SOIL TO THE HYGROSCOPIC COEFFICIENT.

BY F. J. ALWAY.

INTRODUCTION.

It is generally recognized that a mere statement of the total moisture content of a soil gives little or no information as to the amount of water which is available to plants growing upon that soil. To obtain such information it is necessary to first ascertain the nonavailable portion of the soil water. Sachs in 1859 introduced the direct method for the determination of this—allowing plants to grow in flowerpots filled with the soil until they permanently wilted and then determining the amount of moisture remaining. At practically the same time Hilgard developed an indirect method—the determination of the *hygroscopic coefficient* of the soil, which consists in exposing a very thin layer of air-dry soil to an atmosphere saturated with water vapor and kept at a practically constant temperature until the maximum amount of hygroscopic moisture has been absorbed, after which the water content is determined.

Notwithstanding the fact that the descriptions of both these methods were published over fifty years ago, almost all investigators who have occasion to make soil moisture determinations still publish their data in the form of percentages of total water. In field studies where the soil is exceptionally uniform such data may possess definite significance to the individual investigator well acquainted with the particular soil, but usually the data are meaningless to others and often are entirely misleading even to him who has made the moisture determinations. Such data do not permit of the recognition of a particular soil as either relatively *moist* or relatively *dry;* yet practically any farmer can recognize a soil as either moist or dry by merely looking at it and feeling it. That most soil investigators have so long continued to follow a method which does not give as much useful information

RESEARCH BUL. 3, AGR. EXP. STATION OF NEBR.

regarding the amounts of available soil moisture as can be secured by an ordinary farmer using only his eyes, his hands, and a spade or auger, is not so remarkable as it may at first appear. On the one hand, the direct determination of the nonavailable soil moisture is so tedious that in field studies, where a separate determination for every sample might be necessary, the amount of labor involved appears prohibitive.[1] On the other hand, experimental data on the relation of the nonavailable water to the hygroscopic coefficient are very scanty and there has never been a general recognition of the latter as equivalent to the nonavailable moisture. The general failure to recognize that differences in moisture content which are very apparent while the samples are being collected are not to be detected from the tabulated percentages of total water is probably due to the general practice of having assistants or laborers attend to the collecting of the samples.

The lack of a general recognition of the importance of the determination of the hygroscopic coefficient is probably, however, due chiefly to the reaction from the old view of the practical importance to be attributed to the relative amounts of moisture which different soils, when dry, are able to absorb from the atmosphere, a view which originated with Sir Humphrey Davy early in the nineteenth century and was fully accepted by the foremost investigators until 1875. The long acceptance of this erroneous view of the value of the hygroscopicity of soils was due to the prevailing opinion that the amount of water lost by transpiration from a unit area of land was far in excess of the amount of water falling, as rain and snow, upon the same area. This loss had been calculated from pot experiments in which plants had at all times been kept supplied with an abundance of

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[1] A good illustration of the variability of the soil of individual samples from foot to foot and from boring to boring is indicated in the following, which gives the hygroscopic coefficients of soil samples taken from different fields at the same time or from the same field at different times on the H O Ranch, near Madrid, Nebraska:

Depth	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11
Feet											
1	7.8	8.5	8.0	7.5	7.1	7.4	5.9	8.5	7.0	5.3	1.9
2	10.4	9.8	9.8	10.5	10.4	6.1	6.3	10.2	7.8	5.1	1.8
3	10.2	9.8	11.3	9.2	8.0	7.0	6.4	12.4	9.3	3.3	1.7
4	7.0	8.3	7.7	6.9	6.7	7.2	7.1	13.1	13.0	3.0	1.5
5	7.0	6.9	6.4	6.6	6.3	7.1	7.7	12.2	14.2	3.0	1.8
6	7.8	7.4	6.3	6.9	6.0	9.1	9.3	9.0	12.8	1.9	1.9
7	6.9	....	5.9	4.0	4.1	9.1	11.5	9.4		2.7	1.7
8	......	.....	5.1	....	3.9	9.1	9.9	9.2	.....	2.2	1.8
9	..	..	5.9		2.9	7.7	9.0	9.2		3.8	1.5

water, it being assumed that the loss in the field was at the same rate per unit area of surface. The transpired water, thus calculated, exceeded the precipitation and to account for the difference it seemed necessary to assume that the soil could have absorbed and rendered available to vegetation the ever-present water vapor of the atmosphere. Later it was found that the loss of water by transpiration depended upon the degree of moistness of the soil and that, hence, there was no evidence of any such deficit. Experiments by Mayer and by Heinrich indicated that plants were unable to make any use of the hygroscopic moisture and that none of the moisture of the air was rendered available to the plant thru the absorbent power of the soil, and Mayer discouraged even indicating the hygroscopicity of soils on the ground that it would cause confusion if very hygroscopic soils were marked with a defect in regard to the water supply when this was not of much practical significance for the reason that these soils were the very ones that had the highest water capacity.

Following this proof of the falsity of the old conception of the significance of the hygroscopicity of soils came the view, carried to the opposite extreme, that a knowledge of the hygroscopic power of different soils is practically valueless, the question of the usefulness of a knowledge of the relative hygroscopicity of soils being apparently confused with the distinct question of the usefulness to plants of the hygroscopic moisture of the soil.

Loughridge was the first in connection with field studies of soil moisture to determine the hygroscopic coefficients of all the samples dried and to tabulate the *free water* as well as the total water. Loughridge's work first suggested to the writer the determination of the hygroscopic coefficients of the different soil samples, taken in connection with a field study of soil moisture in 1904-1905, after he had found that there was little agreement between the data on the total soil moisture and his field notes. The data on the free water, on the contrary, agreed with the field observations. The results of this field study suggested the pot experiments reported in the following pages. These experiments were carried out in connection with and subordinate to various soil investigations, the object being to determine the relation of the final water content of the soil to the hygroscopic coefficient and to determine to what extent the moisture was removed from the different portions of the subsoil not penetrated by plant roots.

For assistance in the experiments the writer is indebted to Dr. W. D. Bonner, Dr. R. A. Gortner, Mr. G. R. McDole, Prof. R. S. Trumbull and the late Mr. W. A. Wullschleger.

REVIEW OF PREVIOUS WORK.

OLDER VIEW OF THE IMPORTANCE OF THE HYGROSCOPICITY OF SOILS.

Davy considered that the hygroscopic power of soils enabled them to render the water of the atmosphere available to plants and that the relative hygrosopicity of a soil served as an index of the productiveness of land. "The power of soils to absorb water from air is much connected with fertility. When this power is great the plant is supplied with moisture in dry seasons, and the effect of evaporation in the day is counteracted by the absorption of aqueous vapor from the atmosphere, by the interior parts of the soil during the day, and by both the exterior and interior during the night."[1] "I have compared the absorbent power of many soils with respect to atmospheric moisture, and I have always found it greatest in the most fertile soils so that it affords one method of judging of the productiveness of land."[2]

Schübler,[3] who was the first to determine the maximum amount of moisture absorbed by various soils when exposed to an atmosphere almost saturated with water vapor, agreed in the main with Davy's view but pointed out that the power of absorption, considered alone, might be very deceptive as he had found that "a pure, infertile clay absorbs in twelve hours * * * more than a very fertile garden soil."

Liebig[4] accepted Davy's view as to the value of the moisture absorbed from the air. "When in the hot summer the surface of the ground is dry, and there is no replacement of moisture by capillary attraction from the deeper strata, the powerful attraction of the soil for the vapors of water in the air provides the means for supporting vegetation."

Sachs[5] in 1859 distinguished experimentally between the available and the nonavailable water. He grew tobacco plants in three different soils,—a vegetable mold, a loam, and a quartz sand—and found that they wilted permanently, while 12.3, 8.0, and 1.5 per cent respectively of water remained in the soil. The maximum water capacities of the three soils were 46, 52.1, and 20.8 per cent. He made no determination of the relative hygroscopicity of the soils. The considerations leading up to these experiments he stated[6] as follows:

"If one wishes to learn to know the relation of the plant to the soil water it does not suffice to know how much water a certain kind of soil can take up, we must much more know whether and how much of this *the plant* can take up. * * * For this purpose one must determine the degree of moistness of the soil at which the plants no longer are in position to withdraw from it the minimum of their needs, where the roots in the soil no longer can take up so much water as may be necessary to replace the smallest evaporation from the leaves. This takes place when the leaves in a very moist atmosphere, even by night, remain wilted. Wilting by day and in dry air proves only that the leaves give out more than the roots are able to take up in the same time, but it does not prove whether the roots are no longer able to take up any; by strong sunlight the leaves can wilt, even when the roots take up very much and stand in very moist soil. When on the other hand the leaves wilt in moist air and by the absence of light, where their transpiration is almost zero, this proves that the roots are unable to take up even this small quantity and that if the plant should need more it would only suffer so much a greater shortage. When the plant is in this condition, the soil can still contain considerable quantities of water, more or less according to its nature."

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[1] Davy, Sir Humphrey. Agricultural Chemistry, Second Edition, 1814, p. 183.

[2] Ibid., p. 184.

[3] Schübler, G. Grundsätze der Agrikulturchemie, 1830, vol. 2, p. 82

[4] Liebig, J. Letters on Modern Agriculture, 1859, p. 48.

[5] Sachs, J. Ueber den Einfluss der chemischen und physikalischen Beschaffenheit des Bodens auf die Transpiration der Pflanzen. Landwirthschaftlichen Versuchs-Stationen, 1859, vol. 1, p. 235.

[6] Ibid., p. 234. The writer is responsible for the translation.

To test the commonly accepted view as to the importance of the ability of different soils to attract water vapor from the atmosphere Sachs carried out two experiments,[1] one with a scarlet runner plant (*Phaseolus multiflorus*) and another with a tobacco plant. These experiments indicated that a very hygroscopic soil under certain conditions was able to attract enough moisture from an almost saturated atmosphere to maintain the life of plants. In the first experiment, that with the scarlet runner, he took a young plant with three leaves, grown in a very heavy soil in a porous earthen flowerpot, and allowed it to stand without watering until the soil was fully air-dry and the leaves began to wilt. Then the bottom of a high and roomy glass cylinder was covered with a shallow layer of water, an inverted beaker placed in the middle of it, and on the bottom of this the flowerpot placed. The upper opening of the cylinder was closed with a divided glass cover in such a way that only the thin stem of the plant projected thru the central opening in the cover. Thus the leaves were exposed to the air of the room while the soil containing the roots was in an almost saturated atmosphere. The wilted leaves became fresh and remained turgescent during two months (June and July) without ever wilting. No further development took place, the original leaves remaining healthy but no new ones appearing. In the second experiment a tobacco plant with three large leaves was grown under similar conditions but in a soil of vegetable mold. Sachs had expected a more favorable outcome in the latter experiment on account of the greater hygroscopicity of the soil used but the results were similar to those in the first.

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[1] Ibid., p. 236.

Mayer[1] in 1871, altho questioning the correctness of the calculations which showed a transpiration exceeding the precipitation, accepted the old view. "The absorptive power of the soil for water * * * is under all circumstances a *useful soil property,* as it becomes active only when there is an actual scarcity of water in the soil and so acts as a regulator." "The water thus condensed in porous solid bodies conducts itself exactly like other capillary held water and can, for example. when a field soil has in this way condensed water, be taken up by a plant's roots just like that which has entered the small interstices of the soil from the rain or by watering."

RECOGNITION OF THE FALSITY OF THE OLDER VIEW.

Wilhelm,[2] was as early as 1861 inclined to conclude from his experiments that the absorptive power of the soil was useless.

Reisler,[3] according to Hilgard, began, in 1868, the experimental testing of the reality of the accepted importance of the absorptive power of the soil for the development of plants.

Mayer[4] in 1875 reported experiments similar to those of Sachs, using peas, barley, and buckwheat in flowerpots filled with sand, garden soils, marl, and sawdust, the last as representative of very hygroscopic soils. In the case of each he determined both the water content at the time of the collapse of the plant and the hygroscopicity by Schübler's method. He concluded that the power of condensation of the soil does not benefit the plants, as these have already been injured beyond recovery before the soil is able to absorb moisture from the air, and that the transpiration of plants in the field had been greatly overestimated, there being no proof of an actual deficit of water. He recognized that the water remaining in the soil on the wilting of a plant was closely related to the maximum amount of moisture which the soil was able to absorb from an almost saturated atmosphere. He considered this, however, to have little practical importance as "by a remarkable coincidence the most strongly condensing soils are usually those with the highest water capacity and it would probably only cause confusion if we were to mark these soils with a blemish in regard to the supply of water on account of a not very productive correction."[1]

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[1] Mayer, Adolph. Agrikulturchemie, First Edition, 1871, Part II, p. 130. The writer is responsible for the translation.

[2] Wilhelm, G. Der Boden und das Wasser, 1861, Vienna, as reviewed in Hoffmann's Jahresberichte über die Fortschritte der Agrikulturchemie, vol. 5, 1862-1863, p. 18.

[3] Hilgard, E. W. Ueber die Bedeutung der hygroskopischen Bodenfeuchtigkeit für die Vegetation. Forschungen auf dem Gebiete der Agrikulturphysik, vol. 8, 1885, p. 93.

[4] Mayer, Adolph. Studien über die Wasserverdichtung in der Ackererde. Frühling's neue landwirthschaftliche Zeitung, vol. 24, 1875, pp. 87-97, as abstracted in Biedermann's Centralblatt für Agrikulturchemie, vol. 11, 1877, pp. 243-249.

Somewhat previous to Mayer, Heinrich[2] had begun a series of experiments which were similar to those of Sachs but included many additional precautions to make his results more accurate and employed a larger number of different plants and soils. Later[3] he continued his experiments, still further improving his methods. The plants were grown in glass vessels of 80 to 100 c.c., until they had reached considerable development. The room was protected from the direct sunlight and from rapid changes of air, the atmosphere being kept almost saturated with water, and care being taken to insure the soil being as thickly penetrated by roots as possible so that at the conclusion of the experiment all parts of the soil would be equally exhausted of water. On the wilting of the plants in a moist atmosphere they were quickly removed from the soil which was then thoroly mixed for a moisture determination. The maximum amount of hygroscopic moisture which the soils could absorb was determined by exposing them in thin layers, in some cases for weeks, to a saturated atmosphere. He used six soils, ranging in hygroscopic coefficient from 1.15 to 42.30, and found that in no case was the plant able to reduce the moisture content to the hygroscopic coefficient before wilting.

To decide whether plants differed from one another in their ability to exhause the soil moisture, he used nineteen different cultivated plants, including wheat, oats, barley, rye, corn, red clover, alfalfa, and potatoes, and also two plants from dry sandy soils and one swamp plant. From these experiments he concluded that "Neither the different cultivated plants nor those designated as swamp and sand plants differ in their ability to extract water from the soil."

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[1] Ibid., p. 248. The writer is responsible for the translation.

[2] Heinrich, R. Die Absorptionsfähigkeit der Bodenarten für Wasserdampf und deren Bedeutung für die Pflanzen. Landwirtschaftliche Annalen des mechlenburgischen patriotischen Vereins, Neueste Folge, vol. 15, 1876, pp. 353-358 and 361-363, as abstracted in Biedermann's Centralblatt für Agrikulturchemie, vol. 12, 1877, p. 16.

[3] Heinrich, R. Zweiter Bericht über die Verhältnisse und Wirksamkeit der landwirthschaftlichen Versuchs-Station zu Rostock, 1894, p. 29.

STUDIES OF THE HYGROSCOPIC COEFFICIENT BY HILGARD AND LOUGHRIDGE.

Hilgard, soon after being appointed State Geologist of Mississippi in 1858, began a study of the soils of that state, using essentially the methods of chemical analysis employed by Owen and Peter in connection with the geological survey of Kentucky and Arkansas. The most notable change he made in the method was the introduction of the determination of the *hygroscopic coefficient,* altho he did not use this term at that time, it appearing first in 1874.[1] In the case of each soil sample analyzed he determined this first of all. He states:[2] "The methods I have pursued in the quantitative analysis of soils, etc., are essentially those described by Dr. R. Peter in the Third volume of the Kentucky Geological Report. * * * I have substituted for the determination of moisture contained in the air-dry soil (varying greatly within brief periods) that of the moisture absorbed by the same at a fixed temperature if possible, in an atmosphere at the point of saturation with aqueous vapor; which renders the determinations directly *comparable* and seems to offer a very important element in the treatment of soils." He recognized in it an index of the degree of heaviness of a soil.

Details of Hilgard's method were published earliest by Loughridge,[3] who was a student under Hilgard and who continued the study of the soils of Mississippi. The method was described later by Hilgard.[4] Loughridge states: "In beginning the analysis of Mississippi soils in 1859 Dr. Hilgard adopted the following method which has also been adhered to by his successors in this work, in over two hundred analyses made. The soil is pulverized with a rubber pestle. * * * The hygroscopic moisture is determined, after exposing it in a space saturated with vapor in a layer not exceeding 1 mm. in thickness, for 12 hours, by drying at 200° C. in a paraffine bath." Loughridge expressed this as "the hygroscopic moisture from 7° to 21° C." Evidently the terms *hygroscopic coefficient* and *hygroscopic moisture* had been in common use between Hilgard and Loughridge during their early association.

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[1] Hilgard, E. W. Silt Analyses of Mississippi Soils and Subsoils, American Journal of Science, vol. 7, 3d Series, p. 9, 1874. This paper had previously been read at the Portland meeting of the A. A. A. S. in 1874.

[2] Hilgard, E. W. Geology and Agriculture of the State of Mississippi, 1860, p. x.

[3] Loughridge, R. H. On the Influence of Strength of Acid and Time of Digestion in the Extraction of Soils. American Journal of Science, vol. 7, 3d Series, 1874, pp. 20-23.

[4] Bulletin 38, Bureau of Chemistry, U. S. Dept. of Agr., 1893, and Circular No. 6, University of California Experiment Station, 1903.

Subsequently in their work in California they changed the temperature of drying from 200° C. to 110° C. to avoid expulsion of combined water and the partial carbonization of organic matter at the former temperature; this method is still in use by them.

In 1880 Hilgard[1] reported the hygroscopic coefficients of 435 soils from eleven different states and territories, all the determinations having been made by himself or Loughridge in Mississippi or by his assistants at the University of California.

Hilgard,[2] using the results of his studies in the arid portions of California, replied to Mayer's sweeping statements, his conclusions being summarized in the following:

1. "Soils of high hygroscopic power can withdraw from moist air enough moisture to be of material help in sustaining the life of vegetation in rainless summers, or in time of drouth. It cannot, however, maintain normal growth, save in the case of some desert plants.

2. "High moisture absorption prevents the rapid and undue heating of the surface soil to the danger point, and thus often saves crops that are lost in soils of low hygroscopic power."

On Hilgard and Loughridge[3] being associated a second time they seem for the first time to have applied to the study of *soils under drouth conditions* their knowledge of the significance of the hygroscopic coefficient. "In the following pages the *hygroscopic moisture* and the *free water* of the soil are frequently spoken of, the latter being that contained over and above what is held in the hygroscopic condition, and representing that which is considered as free to enter the plant roots and upon which the plant chiefly depends."[4] "The actual amounts (of water) required for particular cultures * * * are found by eliminating the hygroscopic moisture and ascertaining the amount of *free water* present in soils where cultures grew and where they suffered and comparing the results."[5] In this study Loughridge reports upwards of 100 determinations of the moisture in the field—the average of the first 4 feet in each case—stating in each case the percentages of total, hygroscopic, and free water.

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[1] Hilgard, E. W. Cotton Production in the U. S., vols. 5 and 6, Tenth Census of the U. S., 1880.

[2] Hilgard, E. W. Proceedings of the American Society for the Promotion of Agricultural Science, vol. 1, 1882, p. 118. Ueber die Bedeutung der hygroskopischen Bodenfeuchtigkeit für die Vegetation. Forschungen auf dem Gebiete der Agrikulturphysik, vol. 8, 1885, pp. 93-100. Soils, New York, 1906, pp. 199-201.

[3] Hilgard, E. W., and Loughridge, R. H. Endurance of Drouth in Soils of the Arid Region. Report of the Agricultural Experiment Station of the University of California for the year 1897-8, pp. 40-64.—Loughridge, R. H. Moisture in California Soils During the Dry Season of 1898, ibid., pp. 65-96.

[4] Ibid., p. 66.

[5] Ibid., p. 95. Quoted also in Hilgard's "Soils," New York, 1906, pp. 212-218.

Hilgard, as pointed out above, had recognized in the hygroscopic coefficient an index of the heaviness of soils—the expression, in a single value, of the texture of the soil—thus anticipating by fifty years the view of Briggs and McLane[1] as to the desirability in soil classification of a single-valued numerical term expressing a common physical property of agronomic importance.

LATER STUDIES ON THE NONAVAILABLE WATER AND ON THE RELATIVE HYGROSCOPICITY OF SOILS.

Gain,[2] using *Erigeron canadensis*, *Lupinus albus*, and *Phaseolus vulgaris,* allowed the plants, in porous earthenware pots, to wilt and then determined the moisture content of the soil. He used six different soils of which he had determined the "coefficient of hygroscopicity according to the method of Schübler." He found rather irregular differences for the different plants but concluded that different plants behave in much the same manner as regards resistance to drouth.

Soil	Coefficient of hygroscopicity*	Water content when plants wilted
		Per cent
Heath soil	....	9.26 to 11.50
Clay	1.75	7.73 to 11.10
Humus	6.0	5.92 to 6.95
Calcareous sand	0.15	2.90 to 5.23
Garden soil	2.6	1.79 to 2.82
Silicious sand	0.0	0 33 to 0.76

* Gain, following Schübler's example, reported this as the weight of water absorbed by 1,000 grams of soil. To make it conformable with the other data the writer has changed it to a percentage basis.

Mitscherlich[3] carried out a series of experiments similar to those of Heinrich, but allowed the plants to remain undisturbed *until they died,* when he determined the moisture content of the soil. Oats, white clover, red clover, and white mustard were grown on six soils whose hygroscopicity had been very accurately determined *by exposure to an atmosphere in equilibrium with a 10 per cent sulphuric acid solution.* He concluded that plants die as soon as they have removed all except the hygroscopic moisture, as thus determined—which is much below the hygroscopic coefficient as determined by the Hilgard method.

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[1] Briggs, L. J., and McLane, J. W. Moisture Equivalent Determinations and Their Application. Proc. American Society of Agronomy, vol. 2, 1910, p. 138.

[2] Gain, M. E. Action de l'eau du sol sur la vegetation. Revue generale de botanique, vol. 7, 1895, p. 71.

[3] Mitscherlich, A. Landwirthschaftliche Jahrbücher, 1901, p. 410.

Mitscherlich[1] in an exhaustive study of the relation of the relative hygroscopicity of soils to their other properties concludes that a knowledge of the hygroscopicity of soils is of extreme importance. He holds that the determination by Hilgard's method gives results much too high on account of the condensation of moisture on the exposed samples. From theoretical considerations he concludes that soils absorb their maximum amount of hygroscopic moisture when allowed to come into equilibrium with an atmosphere in contact with a 10 per cent sulphuric acid solution.

Hedgcock[2] experimenting with a great variety of plants on six different soils concluded that the ability of plants to take water from the soil varies in an ascending scale from hydrophytes, thru mesophytes, to xerophytes, there being variations not only among genera but also among species and among individuals. He reports no determination of the relative hygroscopicity of the soils used.

Clements[3] has proposed the use of the terms "chresard" and "echard" for the available, or physiological, water content and the nonavailable water content of the soil respectively. "All soils contain more water than can be absorbed by the plants which grow in them. This residual water which is not available for use, varies for different soils. * * * It differs, but to a much less degree from one species to another. A plant of xerophytic tendency is naturally able to remove more water from the same soil than one of mesophytic or hydrophytic character. * * * After one has determined the physiological water for the great groups of soils, it is more or less possible to estimate the amounts in the various types of each." He describes in detail the method of determining the "echard" by pot experiments. Later[4] he states: "This available water, or chresard, differs for the different soils, and, for dissimilar species of plants." No reference is made in either of these two books to the hygroscopic coefficient of soils or to any other means of determining the "echard" of a soil than by the physiological method. "The amount of water that a plant can absorb from the soil can be readily determined only by finding the amount left when the plant wilts completely."[5]

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[1] Mitscherlich, A. Bodenkunde für Land- und Forstwirte, Berlin, 1905.

[2] Hedgcock, G. G. Botanical Survey of Nebraska, vol. 6, 1902.

[3] Clements, F. E. Research Methods in Ecology, Lincoln, Nebr., 1905, pp. 5 and 31.

[4] Clements, F. E. Plant Physiology and Ecology, New York, 1907, p. 9.

[5] Ibid., p. 13.

PREVIOUS STUDIES BY THE WRITER.

In 1904 and 1905, while examining into conditions in the Canadian Northwest[1] for an explanation of the remarkably high yields of small grains obtained on summer-fallowed land, the writer took several sets of soil samples to a depth of 6 feet at the Indian Head Experimental Farm and determined the total water in these. Finding that the percentages of total water did not at all correspond with the field notes, which had been recorded as the samples were taken foot by foot, the hygroscopic coefficients of all the samples were determined, following the example of Loughridge referred to above. The resulting data on the *free water* were in satisfactory accord with the field notes.

In a single experiment, using some surface soil from Indian Head, barley plants were grown in a glass cylinder 10 inches deep. At the end of six weeks water was withheld. After the plants died,[2] the soil at all depths below 2 inches contained 18 to 19 per cent total water. The hygroscopic coefficient, as determined, was found to be 12.

It was concluded that: *a*. In such moisture studies in the field the depth to which moisture determinations should be made depends upon the limit of the root penetration of the crop, being 4 to 5 feet for wheat and oats and 6 to 7 feet for grasses at Indian Head. *b*. Unless the soil under consideration is very uniform a determination of the hygroscopic coefficient of each sample is indispensable, and the determination of this value is extremely important even where the soil is uniform. *c*. A better idea of the moisture condition of the soil at Indian Head could be obtained by a casual examination in the field, using a soil auger, than by drying and weighing samples unless the hygroscopic coefficient of each sample was determined. *d*. The storage capacity for available water of the two soil types studied amounted to from 5 to 7 inches of rainfall for wheat and oat crops. *e*. Comparatively little water is lost by direct evaporation from the subsoil below the surface 12 inches of soil. *f*. In semiarid regions roots penetrate to the stored water and the latter does not need to be elevated to the surface foot of soil in order to become available. *g.* In dry-land experiments tillage operations should be governed by actual determinations of the moisture conditions of the subsoil, but a fair idea of these conditions is revealed to the experienced eye and hand without the weighing or drying of samples.

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[1] Alway, F. J. Studies on the Soils of the Northern Portion of the Great Plains Region—The Second Steppe. American Chemical Journal, 1906, vol. 31, p. 580.—Some Soil Studies in Dry Land Regions—A paper read at the Second Annual Meeting of the Cooperative Experiment Association of the Great Plains Area, held at Manhattan, Kansas, June, 1907, and published in Bul. 130, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1908, p. 42.—Studies of Soil Moisture in the Great Plains Region. Journal of Agricultural Science, 1908, vol. 2, p. 333.

[2] Briggs, L. J., and Shantz, H. L., have incorrectly referred to this as tho the moisture had been determined when the plants wilted. The Wilting Coefficient for Different Plants and its Indirect Determination, Bulletin 230, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1912, p. 66.

To account for the failure of very heavy crops, maturing during almost rainless weather, to reduce the moisture as low as the hygroscopic coefficient it was suggested that the lower limit of water available for the normal growth of plants was considerably higher than the hygroscopic coefficient—4.5 to 6.0 per cent—depending upon the value of the hygroscopic coefficient—for the two soil types in question in that particular study. For the portion of the soil moisture above this lower limit the designation "water probably available for the support of normal plant growth" or "X water" was used.

Several years after the publication of the results of this investigation the writer found that the slight modification which he had introduced into Hilgard's method—the employment of shallow pasteboard trays to hold the glazed paper instead of placing the latter directly on the wooden shelf—while giving concordant results with duplicate determinations made at the same time or in the same manner at different times, invariably gave values much below the true coefficients. Thus the results while showing the relative hygroscopicity of different samples gave too high a free water content. Unfortunately, on removing to the University of Nebraska the writer had discarded all the samples taken at Indian Head for moisture determinations. However, part of another series[1] on which determinations of the hygroscopic coefficient had been made in the same way and only a few weeks later had been saved. New determinations on the latter gave values 1.5 times as high as the earlier ones. It is evident that had the original determinations of the hygroscopic coefficient of the different samples been correct the importance of the determination of the hygroscopic coefficient would have been much more distinctly shown and there would have been a still closer connection between the data on the free water content of that portion of the soil penetrated by plant roots and both the field notes at the time of sampling and the previous history of the fields.

Later field studies[2] at widely separated points in the semiarid region of summer-rains in the United States indicated that the generalizations previously shown to apply to studies of soil moisture in Saskatchewan were equally applicable to the whole of the semiarid region of summer rainfall from the Saskatchewan River on the north to the Mexican boundary on the south. "The depth to which samples should be taken should extend at least as far as the plants develop roots freely or as far as the moisture descends from the surface. This depth can in most cases be approximately determined by a field examination of the soil. Soils of this region are characterized by their ability to be reduced by the native vegetation and by many annual crop plants to a characteristic easily recognized, dry condition. This state of dryness seems the normal condition in the more southerly regions, while in the most northerly it may be found only at the time of the maturing of the plants. This property facilitates in most cases the ready recognition of the moisture condition by a mere field examination with the soil auger."

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[1] Alway, F. J., and McDole, G. R. Studies on the Soils of the Northern Portion of the Great Plains Region—The Distribution of Carbonates on the Second Steppe. American Chemical Journal, 1907, vol. 32, p. 275.

[2] Alway, F. J. Moisture Studies of Semiarid Soils. Report of Winnipeg meeting of the British Association for the Advancement of Science, 1909,

RECENT STUDIES BY BRIGGS AND SHANTZ.

Briggs and Shantz[1] have recently published the results of an extensive series of pot experiments in which they have fully utilized the results of all previous studies along the same line. Also, they have applied the conclusions arrived at from these pot experiments to field studies of soil moisture, but have as yet published but few data on the latter. In their pot experiments they have, like Heinrich, used small glass vessels[2] and allowed the soil to become as thickly penetrated by roots as possible, after which it has been allowed to stand fully protected from evaporation until the plants wilted permanently. The per cent of water remaining in the lower two-thirds of the soil mass, where the roots are most abundantly developed, they designate the *wilting coefficient*.

They have met the various obstacles that stood in the way of accuracy by various ingenious methods. Further, they have attempted to determine the relation which holds between the wilt-

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p. 698. Photograph reproduced in Widtsoe's "Dry Farming," 1911, p. 96. The data of the experiment described below as that of 1909 (page 33) were presented in the paper.

[1] Briggs, L. J., and Shantz, H. L. A Wax Seal Method for Determining the Lower Limit of Available Soil Moisture, Botanical Gazette 51, 1911, p. 210.—The Wilting Coefficient and its Indirect Determination, Botanical Gazette 53, 1912, p. 20.—The Wilting Coefficient for Different Plants and its Indirect Determination, Bul. 230, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1912.—Application of Wilting Coefficient Determinations in Agronomic Investigations, American Society of Agronomy, November, 1911, vol. 3, p. 257.

[2] Briggs and Shantz have used ordinary drinking glasses.

ing coefficient and other physical values of soils, viz, the hygroscopic coefficient as determined by Hilgard, the maximum water capacity as determined by Hilgard, the moisture equivalent as defined by Briggs and McLane, and the mechanical analysis, using the classification of separates employed by the Bureau of Soils.

They conclude, that, while there are slight differences for different plants and that these differences hold with the various soils, the wilting coefficient is practically independent of the plants used and is not distinctly influenced by the age of the plant, by the humidity of the air, by the light intensity or by the moisture content of the soil during the growth of the plant; when the leaves curl or drop the soil moisture is not at the wilting coefficient but below this and above the hygroscopic coefficient; the death point, however, varies with the plant used, some plants dying much more quickly after wilting than others. After the death of the plant the soil still continues to lose water thru the tissues of the plant. "The plants during the drying stage act simply as a medium for the transfer of water and, while the rate of loss is reduced, the final result is the same as if the air and soil were in direct contact." The wilting coefficient "practically marks the cessation of growth and so constitutes a datum from which the water content available for growth in a particular soil may be determined when the total water content is known."

From studies of the relation between the wilting coefficient and other physical properties they have deduced the following formulas, which show also the probable error:

$$\text{Wilting coefficient} = \frac{\text{moisture equivalent}}{1.84\ (1 \pm 0.007)}$$

$$\text{Wilting coefficient} = \frac{\text{hygroscopic coefficient}}{0.68\ (1 \pm 0.018)}$$

$$\text{Wilting coefficient} = \frac{\text{moisture-holding capacity} - 21}{2.90\ (1 \pm 0.021)}$$

$$\text{Wilting coefficient} = \frac{0.01 \text{ sands} + 0.12 \text{ silt} + 0.57 \text{ clay}}{1 \pm 0.025}$$

As the direct determination of the wilting coefficient is more difficult and time-consuming than the indirect method, they conclude that the former may be altogether replaced by one of the latter, of which they prefer the determination of the moisture equivalent. It will be seen from the second formula that they place the wilting coefficient at almost one and a half times the hygroscopic coefficient.

They thus really divide the total water content of any particular sample of soil into three parts:

1. Water available for growth—the difference between the total water content and the wilting coefficient.
2. Portion of the available water not available for growth—the difference between the wilting coefficient and the moisture content of the soil when in equilibrium with the air.
3. Nonavailable water—the moisture content of the soil when in equilibrium with the air, or, in other words, the water content of the air-dry soil.

They make no distinction between the physiological importance of the portion of the water between the wilting coefficient and the hygroscopic coefficient and that of the portion between the hygroscopic coefficient and the air-dry condition.

In their latest publication[1] they modify their earlier statement in regard to the significance of the wilting coefficient, deduced from their studies using drinking glasses, when applied to field conditions or to experiments in which large pots are used.

"The results of some of the soil moisture determinations made on the Great Plains during the summer of 1911, which was extremely dry, indicate that a crop is capable, under certain conditions, of reducing the moisture content of a part of the soil below the wilting coefficient, before the crop actually wilts. * * * It follows that the amount of moisture available for growth may be somewhat greater than that calculated by the use of the wilting coefficient as a datum.

"It often happens under field conditions and also when plants are grown in large pots that at the approach of a drouth the lower leaves die very gradually. This self-pruning continues in extreme cases until the entire leaf area is dead. Often the general wilting of the plant can not be observed during the whole process. Under these conditions the wilting point is at best indefinite, and the soil moisture content is usually reduced far below the wilting coefficient before the death of the plant. The water which is removed from the soil after the moisture content has been reduced to the wilting coefficient may result in some growth but this is so small in proportion to the water consumption that it is of little practical value from the standpoint of crop production."

Their use[2] of the data from the single pot experiment with barley plants described by the writer and their presentation of the means advocated by him for the estimation of available moisture in soils are inaccurate, as is shown elsewhere in this publication.[1]

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[1] Application of Wilting Coefficient Determinations in Agronomic Investigations, American Society of Agronomy, Nov., 1911, vol. 3, p. 257.

[2] Bulletin 230, Bureau of Plant Industry, p. 66.

GENERAL DESCRIPTION OF THE EXPERIMENTS.

The experiments were carried out in a greenhouse using watertight galvanized iron cylinders. Except in the case of those with desert legumes the cylinders were 6 feet long and 6 inches in diameter, containing known amounts of soil and of water. In these, seeds were planted and the plants allowed to grow, without further addition of water, until they died. On the death of all the plants in a cylinder it was opened and the moisture content determined in 3-inch sections. The distribution of roots in the subsoil was carefully observed and in the later experiments these were removed, photographed and weighed.

SOILS USED.

Some of the soils used were from the semiarid western portion of Nebraska, some from the humid eastern portion, and the others from the intervening portion of the *transition region.* The physical character of the soils used is shown by their hygroscopic coefficients given in Table 1.

PLANTS GROWN.

Red Fife wheat was grown in the experiments of all four years, milo and Mexican beans in the last two, and Kubanka wheat, corn and some perennial desert legumes each in only one year. The last mentioned were *Prosopis velutina, Acacia Greggi* and *Acacia constricta.*

GREENHOUSE USED.

The only greenhouse available for the experiments was an old, poorly ventilated one. The ventilators in this were immediately above the only portion of it in which the cylinders could be placed. As any rain falling on the cylinders would have seriously interfered with the experiments, the ventilators were kept closed during threatening as well as during rainy weather. A steam-main, which led to another building, and in which the steam was kept at high pressure day and night until warm weather set in, increased the difficulty of keeping down the maximum temperature. The use of whitewash on the glass panes of the greenhouse had to be abandoned, as the wheat plants would be

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[1] Footnote 2, p. 116.

TABLE 1.—*Hygroscopic coefficients of soils used in the different experiments.*

	1908	1909		1910	1911						
Depth	W. Neb.*	W. Neb.*	E. Neb.	H O*	H O*	Wauneta	McCook	Holdrege	Hastings	Lincoln	Surface Soil
Feet											
1	10.0	8.5	10.0	10.1	10.0	9.2	9.4	10.1	10.7	12.1	11.3
2	10.9	8.8	11.6	5.6	5.6	9.5	11.0	11.7	13.2	15.3	11.3
3	9.9	10.4	15.1	5.6	5.6	9.9	9.6	12.0	11.7	14.6	11.3
4	7.5	9.3	13.9	5.6	5.6	10.1	9.0	10.6	11.5	13.2	11.3
5	....	7.4	13.6	5.6	5.6	9.5	8.8	9.7	10.8	13.2	11.3
6		7.1	12.5	5.6	5.6	8.6	8.4	9.6	10.5	13.5	11.3

* These soils are from Madrid, near the western edge of Nebraska.

found soon after its application to be prostrated, but they recovered when it was removed. Thus the windows were left without protection against the direct rays of the sun. As a result the temperature inside the greenhouse rose very high on hot, sunny days—a daily maximum of over 100° F. being the rule rather than the exception.

During the preliminary experiment, in 1908, no record was kept of the temperature, humidity, or rate of evaporation in the greenhouse. During the latter half of the experiment of the following year a record was kept of the evaporation from a free water surface, using two cylindrical jars, one of glass 4 inches in diameter and the other of white stoneware 6 inches in diameter. These were placed level with the tops of the cylinders, being supported on a table covered with white paper. They were filled to a mark one inch from the top and at the end of each week water was added to raise the water to this mark. The evaporation record of that year is important in that it constitutes the only data recorded which indicate the relation of the general conditions in the greenhouse during the experiment of 1909 to those of the following two years. In the experiment of 1910 the evaporation from a free water surface was determined from March 12 on, using four glass jars like the glass jar of the preceding year and similarly supported. They were placed at the four corners of the framework enclosing the metal cylinders. There were no important differences between the different jars in the amount of evaporation from week to week. In the 1911 experiments two glass jars similar to those of the preceding year were used but they were sunken in the soil surrounding the cylinders so that the mark on each was level with the surface of the soil as shown in the case of the one in figure 21. It will be seen from Table 2 that the recorded rate of evaporation in 1911 was two or three times as great as in the preceding two years. This was due in part to the increased air movement in the greenhouse on account of better ventilation. The rate of evaporation recorded in this year appears remarkably high.[1] A record[2] of the rate of evaporation in the near-by open air was kept by the U. S. Weather Bureau, but unfortunately for only part of the period, the evaporating pan being less than 200 yards from the greenhouse. The data from this record are included in Table 2.

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[1] Similar high rates have been recorded in Australia where an evaporation of from 140 to 160 inches in 12 months was recorded, using small evaporating cylinders. Report of Meteorological Observations for Western Australia in 1907, p. 7 and p. 110.

[2] Loveland, G. A., and Perin, S. W. Evaporation from a Free-Water Surface at Lincoln, Nebraska. Twenty-fifth Annual Report of the Nebraska Experiment Station, 1912, p. 193.

TABLE 2.—*Evaporation from a free water surface in the greenhouse and in the adjacent open air.*

	In greenhouse			In open air	
	1909	1910	1911	1909	1910
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
March	......	4.7†	......	......	......
April	......	5.7	5.5§	4.7	6.7
May	4.0*	4.7	8.2	5.9	5.6
June	4.0	3.9‡	13.7	6.7	7.8
July	4.2	......	13.0	6.0	7.4
August	......	......	8.0	......	......
September	......	......	6.0	......	......

* From the 3d. † From the 12th. ‡ To the 21st. § From the 12th.

TABLE 3.—*Relative humidity at 5 p. m. in the greenhouse and in the open air.*

		In greenhouse	In open air	Difference	
1910					
April	Second decade	48	49	..	1
	Third decade	33	29	4	..
May	First decade	55	58	..	3
	Second decade	54	52	2	..
	Third decade	49	47	2	..
June	First decade	51	51	0	..
	Second decade	43	33	10	
1911					
March	First decade	43	55	..	12
	Second decade	39	33	6	..
	Third decade	39	...*	..	..
April	First decade	41	...*	..	..
	Second decade	42	40	2	..
	Third decade	50	48	2	..
May	First decade	48	49	..	1
	Second decade	49	43	6	..
	Third decade	59	54	5	..
June	First decade	40	36	4	..
	Second decade	41	38	3	..
	Third decade	38	32	6	..
July	First decade	37	33	4	..
	Second decade	45	39	6	.
	Third decade	40	37	3	..
August	First decade	42	44	..	2
	Second decade	49	47	2	..
	Third decade	46	...*	..	..
September	First decade	57	64	..	7
	Second decade	56	58	..	2
	Third decade	57	65	..	8
Highest humidity recorded on any day		85	88		
Lowest humidity recorded on any day		22	15		

* Record incomplete.

Thruout the latter portion of the experiments of 1910 and 1911 the humidity was recorded daily at 8 a. m. and at 5 p. m., using a wet-bulb thermometer. The mean humidity at 5 p. m. for monthly decades is given in Table 3. The data for the humidity in the open air at the same hour are from the record of the Lincoln station of the United States Weather Bureau, which is only three miles from the Experiment Station. The differences in general are not great, the humidity being somewhat lower in the open air than in the greenhouse, notwithstanding the high temperatures which prevailed in the latter, due probably to the presence in the greenhouse of a number of pots with plants belonging to other experiments, to which water was applied daily. During the first and the last three decades in 1911 there were none of the watered pots in the greenhouse and during these two periods the air was much drier than that outside.

In the experiments of 1910 and 1911 the daily maximum and minimum temperatures were recorded from the time the experiments were well started until the plants died. The daily maxima are shown in Table 4 and the daily means—the average of the maximum and the minimum—in Table 5. The thermometer was hung at the level of the cylinder tops in a well ventilated wooden shelter, placed at one end of the row of cylinders. When in 1910 it was found that under the conditions prevailing the plants in moist soil apparently suffered no ill effects from temperatures up to 110° F., no effort was made to keep the daily maximum temperature below 105° F. As soon as the temperature reached this point steps were taken to prevent it rising higher. While the means of ventilation in the greenhouse were entirely inadequate to keep the maximum temperature below 100° F. on bright days, it could be kept below 112° F. except under very unusual conditions. The occasions in 1910 on which it rose above this were afternoons on which after cloudy, threatening weather the sun came out very bright. The ventilators having been closed to keep out any rain from the threatened storm and not being opened on the appearance of the sun, the temperature rose rapidly. For this reason Sundays were especially the days of high temperatures—as May 8 and 29 and June 12, 1910. The high temperature of June 12, 1910, viz: 124° F., practically terminated the experiment of that year, all plants dying rapidly after this. The very high temperatures recorded in 1910 were usually of short duration, because as soon as a visit to the greenhouse showed the temperature to be very high means were taken to quickly lower it.

TABLE 4.—*Maximum temperature in the greenhouse, for each day.*

Date	1910				1911							
	March	April	May	June	February	March	April	May	June	July	August	Sept.
1	......	109	110	109	....	105	100	74	109	124	103	109
2	......	100	109	93	......	108	106	93	113	119	108	101
3	.....	110	96	82	.....	90	76	89	113	124	98	92
4	..	104	96	87	...	95	78	94	125	120	110	99
5	......	97	74	105	......	108	94	95	115	130	109	96
6	......	105	56	102	......	102	82	96	101	109	112	100
7	......	95	98	88	.....	115	94	98	106	114		86
8	......	110	120	97	.....	83	91	109	109	114	112	72
9	.....	106	104	96	......	90		110	112	115	118	88
10	.....	109	105	89	....	95		110	104	112	117	96
11	....	108	112	104	......	99		100	100	112	104	98
12	......	90	101	124	....	99		92	102	108	114	98
13	......	98	90	112	......	86		98	109	111	115	104
14	......	100	95	112	.....	96	95	104	105	112	116	98
15	......	75	80	104	......	92	89	104	114	103	120	98
16	106	88	88	109		99	98	104	113	110	119	88
17	104	90		112		94	92	107	100	102	107	98
18	99		99	116	.....	94	95	114	102	99	107	100
19	98	110	87	......	......	108	86	101	106	95	98	98
20	110	110	108		92	100	88	86	112	110	102	89
21		108	88		96	98	107	88	115	102	96	78
22	106	86	90		104	94	105	93	117	114	90	86
23	98	88				99	100	107	114	110	90	90
24	106	102	97	..	.....	102	95	110	118	92	97	84
25	102	98	102	.....	109	101	94	115	116	102	98	78
26	89	105	80	....	98	108	85	116	114	109	100	76
27	116	109	72	.....	82	92	93	101	110	103	89	98
28	93	115	96	.....	104	104	100	96	99	110	94	95
29	102	112	117	...	.....	104	94	100	113	113	91	86
30	76	98	109	.....	....	99	93	106	114	113	95	74
31	96		112	......	.....	95	..	110	......	113	110	......
Av.	100	101	96	101	.....	98	93	100	110	110	104	92

TABLE 5.—*Mean temperature in the greenhouse, for each day.*

Date	1910				1911							
	March	April	May	June	February	March	April	May	June	July	August	Sept.
1	......	79	82	83	......	88	87	59	90	104	85	89
2	......	77	77	80	......	86	90	68	94	101	87	87
3	......	86	67	71	......	87	74	72	95	106	84	79
4	......	80	71	72	......	86	69	72	101	101	89	84
5	......	72	64	81	......	94	75	73	101	109	89	87
6	......	74	53	83	......	87	76	78	83	92	......	85
7	......	77	79	75	......	94	77	82	88	95	91	75
8	......	82	85	79	......	81	......	90	92	98	91	67
9	......	77	75	79	......	83	......	92	95	94	96	76
10	......	83	81	76	......	84	......	92	91	95	99	82
11	......	82	86	81	......	86	......	80	83	95	89	85
12	......	77	76	92	......	80	......	75	83	90	93	84
13	......	76	64	89	......	84	76	82	86	93	96	90
14	......	64	77	88	......	84	78	87	87	91	96	88
15	......	71	69	86	......	80	78	89	93	86	97	77
16	78	71	68	91	......	84	77	88	94	88	96	81
17	79	73		92	......	83	78	89	88	84	91	87
18	76		74	94	......	82	77	95	88	82	90	80
19	69	87	75	......	......	87	68	89	86	80	85	69
20	80	79	81	......	80	91	70	75	88	86	87	69
21	83	87	73	......	82	89	80	73	95	86	84	68
22		68	71	......	92	87	82	72	94	91	81	75
23	80	64		......	......	84	76	82	95	92	76	76
24	80	73	75	......	......	90	71	87	97	76	79	70
25	76	71	82	......	89	87	73	94	98	81	79	66
26	76	74	68	......	88	82	70	93	99	85	80	86
27	87	92	66	......	76	84	77	86	88	88	77	83
28	72	89	78	......	89	83	83	81	84	92	72	83
29	85	92	87	......	......	88	79	81	95	90	71	76
30	58	76	85	......	......	82	77	87	98	95	78	68
31	79	......	86	......	......	84	......	90	......	95	87	......
Av.	77	78	75	83	......	85	77	82	92	91	86	79

In the 1911 experiment conditions were much more unfavorable on account of the extremely high temperatures prevailing out of doors. In that year the ventilation of the greenhouse had been so much improved that for ordinary seasons it might have proved adequate, but during the very hot weather of June and July the temperature out of doors on many days rose above 100° F., while on July 5 it rose to 110° F. On that day it reached 130° F. in the greenhouse. This temperature, which did not last long, was not sufficiently high to injure well-watered plants in the same greenhouse.

Suspecting the correctness of the remarkably high temperatures recorded by the maximum thermometer, it was tested at various times, both in 1910 and 1911, by placing, during the hottest part of the day, a number of accurate thermometers in various parts of the greenhouse and protecting them all both from the direct rays of the sun and from the heat reflected by the brick walls of the greenhouse. However, nothing was found to justify any assumption of inaccuracy in the temperature data. The high maximum temperatures during the early part of each season were due to the presence of the steam-main mentioned above

DETERMINATION OF THE SOIL MOISTURE.

Each 6-foot cylinder was opened as soon as convenient after removing the last of the plants from it. About two-thirds of the cylinders were opened on the same day that the last plant was removed, but with the others there was an interval varying from 2 to 16 days. It is probable that no appreciable amount of moisture was lost from below the first foot during this interval. and that the moisture conditions were practically the same at the time the cylinders were opened as they were when the last plant died and was removed.[1] It is also improbable that any considerable loss of moisture occurred even from the first foot, as in all the cylinders bearing plants the soil of the surface foot was already very dry and was underlaid by at least one foot of comparatively dry subsoil.

In order to remove the soil from a six-foot cylinder for moisture determinations the cylinder was placed on a table and split lengthwise by shears, 3 inches at a time. (Figure 1, *b*.) The soil from this section was quickly and thoroly mixed and a sample for the moisture determination placed in a pint jar which was then sealed. After the samples had been secured from the whole of the cylinder, moisture determinations were made, using 100- or

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[1] Alway, F. J., and Clark, V. L. A Study of the Movement of Water in a Uniform Soil under Artificial Conditions. Twenty-fifth Annual Report of the Nebraska Experiment Station, 1912, p. 255.

200-gram portions, the contents of each jar being thoroly mixed before removing any of the soil. The samples were dried in an electric oven, kept at 110° C., thru which a rapid current of air was kept passing. In the experiments of 1909 and 1910 all determinations were made in duplicate, using 100-gram samples, but in those of 1911 a single determination of each was made, using a 200-gram sample. As in such a study the thoro drying of the samples is extremely important, the following method was followed to insure its completeness. In the earlier determinations, after the samples, 50 to 60 in all, had been in the oven for 12 hours, five or six from different parts of it were removed and allowed to cool in a desiccator. These were weighed, returned to the oven and left there for from 5 to 12 hours longer when they were again cooled and weighed. If no appreciable loss in weight occurred after the first weighing it was assumed that all the other samples were dry, they having been in the hot oven all the time. If a loss in weight occurred, however, the drying was continued until two successive weighings showed no appreciable change of weight. In the later determinations, instead of using the above method of control, several 200-gram samples taken from a large sample of known moisture content were placed in the oven along with the samples from the cylinders. If after 12 hours in the oven these control samples were found to be fully dried the heating was discontinued, but if not they were returned and weighed at intervals until thoroly dried, the cylinder samples being left in the oven undisturbed until the control samples were dry. The former thus had a longer exposure in the oven than the latter. This modification of the control greatly shortened the time required for the drying, as usually the samples were fully

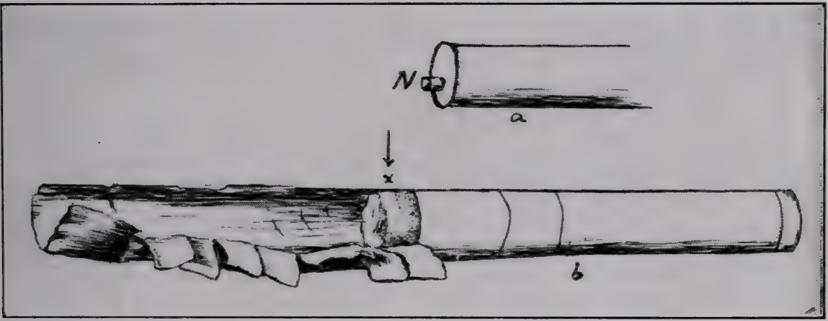

Fig. 1. Cylinders used in experiments of 1909 to 1911. *a.* Lower portion with nipple N. *b.* Manner of opening cylinder in 3-inch sections. At x is shown a 3-inch section of soil ready for removal.

dried at the end of 12 hours, thus permitting two charges, instead of a single charge, to be dried every 24 hours. In the tables in the following pages the amounts of water are expressed as percentages of the dry soil.

FREE WATER.

The free water represents the difference between the total water and the maximum hygroscopic water (hygroscopic coefficient). The soil moisture in the following tables is expressed usually as the free water only but in a few both the total water and the free water are given. In all cases the total water may be found by simply adding the free water to the hygroscopic coefficient.

An expression of free water alone is almost as meaningless as that of total water alone. Thus corn plants may be dying in a soil with a hygroscopic coefficient of 15 and containing 3 per cent free water while plants of the same kind in a soil with a hygroscopic coefficient of 0.8 may be very vigorous with only 1.0 per cent free water. For this reason in order to give tables of free water their full significance there should at the same time be given also corresponding tables of hygroscopic coefficients or of total water. Any two of the three tables are sufficient but some will find a certain combination the most satisfactory and others another. The writer prefers the statement of free water and hygroscopic coefficient, but those who have made many determinations of total water and none of free water will, at least at first, find the statement of total water along with the hygroscopic coefficient to have more significance for them.

Total water — hygroscopic coefficient = free water.

The hygroscopic coefficients of the soil samples were determined by the Hilgard method with a slight modification. Instead of using glazed paper to hold the soil, flat aluminum trays were employed. An extensive study of the determination of hygroscopic moisture had shown that this modification of the Hilgard method gives concordant and reliable results and also that the modification used in determining the hygroscopic coefficients as reported in previous publications[1] gave results much too low. The discussion of methods for the determination of the hygroscopic coefficient is reserved for a future publication.

For the determination of the hygroscopic coefficients the individual 3-inch sections were not used, but the determination was made on a sample of the bulk soil used, it being taken at the time of filling the cylinders. Thus in the case of the 8 cylinders of the experiment of 1909, in which 16 different soils were used, the hygroscopic coefficients of these 16 were determined and used in calculating the free water in the 192 individual sections. This may account for some irregularities in the free water content of sections adjacent to the dividing line between two different soils. Thus, for example, in the case of cylinder I in Table 8 (p. 41) in the lowest section of the fourth foot there is shown only 0.2 per cent free water compared with 1.1 per cent in the section above and 1.7 per cent in the section below. As the soil of the fourth and fifth feet had hygroscopic coefficients of 9.3 and 7.4 respectively, an error of one inch in filling the cylinders or in removing the sections would account for the irregularity. In such cases no attempt has been made to increase the regularity shown in the distribution of free water by making determinations of the hygroscopic coefficient of any of the individual 3-inch samples.

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[1] Alway, F. J., and McDole, G. R. Studies on the Soils of the Northern Portion of the Great Plains Region: the Distribution of Carbonates on the Second Steppe. American Chemical Journal, vol. 32, 1907, p. 275.—Alway, F. J. Some Soil Studies in Dry-Land Regions. Bul. 130, Bureau of Plant Industry, U. S. D. A., 1908, p. 360. Studies of Soil Moisture in the "Great Plains" Region. Journal of Agricultural Science, vol. 2, 1908, p. 333.

In the tables of moisture data the water content of the thin sand layer, about 1 inch in thickness, which was placed in the bottom of each 6-foot cylinder, is not reported for the reason that the sand in the process of removal became mixed with the overlying soil in almost all cases, thus greatly altering the hygroscopic coefficients of the samples as actually dried and the amounts of free water, so rendering the data quite meaningless, unless a separate determination of the hygroscopic coefficient of each sample had been made. The hygroscopic coefficient of this sand was 0.5.

WILTING COEFFICIENT.

The *wilting coefficient* very frequently referred to in the following pages is that defined by Briggs and Shantz.[1] In no case[2] has it been determined directly, it having been calculated from the hygroscopic coefficient using the formula given by Briggs and Shantz, viz:

$$\text{Wilting coefficient} = \frac{\text{hygroscopic coefficient}}{0.68}$$

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[1] See p. 18.

[2] Dr. Briggs has kindly determined for the writer the moisture equivalent of the soil used in the largest number of experiments—the H O Subsoil (p. 47). Five determinations of the moisture equivalent gave an average of 14.2, from which the wilting coefficient of 7.7 and the hygroscopic coefficient of 5.25 is found by the formulas of Briggs and Shantz (p. 19). As the figures had been completed before receiving the data from Dr. Briggs, the wilting coefficient 8.2, calculated from the hygroscopic coefficient 5.6, as determined by the writer, is used in the various figures showing the moisture conditions in the cylinders in which H O Subsoil was employed.

DETERMINATION OF THE DRY MATTER OF THE CROPS.

In the case of each cylinder all the thinnings, fallen leaves, and dead plants were saved in a covered jar until all the plants had been removed. The seeds, if any were present, were counted and weighed; the data on the dry matter of these, reported in the various tables, were calculated on the assumption that the seed contained 10 per cent of water. After removing the seed the rest of the crop was dried at 110° C. and weighed.

PRELIMINARY EXPERIMENT.

In 1908 two cylinders filled with a semiarid soil were planted with Red Fife wheat. Each was 4 feet long and 6 inches in diameter, consisting of two lengths of sewer-pipe fastened together with cement, the latter being coated with paraffine as soon as dry. The bottom of each, likewise made of cement coated with paraffine, carried a one-hole rubber stopper. The cylinders were filled with air-dry soil from the H O Ranch, which is located at Madrid, Perkins County, near the western border of Nebraska. Six bulk lots of soil were used, viz. the first 4, the second 4, and the third 4 inches of the first foot, and the whole of the second, the third, and the fourth foot.

The soil was placed in the cylinders in its natural order. All but the surface inch was added in small portions and tamped with a two-inch rubber stopper on the end of a three-eighths inch iron gas-pipe. The surface soil was covered with a layer of absorbent cotton and water added until seepage thru the one-hole rubber stopper began. Then the addition of water was discontinued and the excess allowed to drain away until seepage ceased, after which the hole in the rubber stopper was closed by means of a glass plug. The absorbent cotton was removed, five sprouted kernels of Red Fife (spring) wheat, from the Experimental Farm at Indian Head, Saskatchewan, were planted one inch deep in the moist soil and the surface inch of air-dry soil was added.

The cylinders were placed in the greenhouse on the day the seed was planted, April 15, and given no more water. They were not sunken below the level of the floor and so were fully exposed to the heat of the sun's rays. At the end of ten days the plants were thinned to the most vigorous two in each cylinder. These developed normally until near the end of May when the plants became prostrated. Thinking the experiment a failure no attention was paid to the plants until three weeks later, when it was found that they had quite recovered and were putting forth heads. The whitewash which had been applied to the glass panes shortly before the injury was first observed had been largely removed by heavy rains; this suggested a connection between the injury to the wheat and the presence of whitewash on the glass. On July 10, 86 days after planting, the 4 plants were quite dead. They had each reached a height of about 21 inches and had each formed one spike, but only one had formed seed and this bore only two badly shrunken grains. The cylinders were split lengthwise and the soil examined for roots. These were found to reach to the bottom of the cylinders. The weight of dry matter in the two plants from the one cylinder was 3.5 grams and in those from the other 4.0 grams.

As, on opening the cylinders, it was found that in each a crevice had developed between the soil column and the cylinder wall, extending from the surface almost to the bottom of the cylinder, thus allowing comparatively free circulation of air and consequent loss of water from the sides of the soil column by direct evaporation, the moisture data have been discarded as valueless. In all later experiments this source of error has been carefully guarded against by watching for the first appearance of such crevices and at once filling them with fine, dry soil.

GROWTH OF WHEAT ON SEMIARID SOIL COMPARED WITH THAT ON HUMID SOIL. EXPERIMENT OF 1909.

In this experiment Red Fife wheat was grown in 6 cylinders, 3 filled with soil from humid eastern Nebraska and 3 with soil from semiarid western Nebraska, all having been saturated with water previous to the planting of the seed. As checks two other cylinders, the one filled with the humid soil and the other with the semiarid soil, were left unplanted but otherwise treated like the six planted cylinders.

The cylinders used in the experiment were of galvanized iron, being 6 feet long, 6 inches in diameter, closed at the bottom and soldered to make the seams water-tight. In the bottom of each was a nipple carrying a one-hole rubber stopper to permit of drainage while the soil was being saturated; a glass plug placed in the hole in the stopper rendered the cylinder water-tight. Before filling the cylinders with soil each was filled with water to test the tightness of the seams. The general construction of the cylinders is shown in figures 1 and 2. The latter illustrates one of the difficulties of working with such tall cylinders; thus, it was necessary to carry the cylinder into the open in order to photograph it, the roof of the greenhouse being too low.

The semiarid soil was from the same prairie field on the H O Ranch as that used in the 1908 experiment, but taken to a depth of 6 feet, being removed from the excavation in eight portions—

the first, second, and third 4 inches of the first foot, and the second, third, fourth, fifth, and sixth foot. The 8 bulk soils were placed in separate sacks for shipment to this Experiment Station, where each, in a dry condition, was thoroly mixed. The humid soil was from the Experiment Station Farm, at Lincoln, the 8 portions being taken at the depths corresponding to those of western Nebraska soil.

The soils were placed in the cylinders in their natural order—that is, the sixth foot first and the first four inches last. The weight of each bulk soil placed in the different cylinders was recorded and a sample was saved for the determination of the moisture content and of the hygroscopic coefficient. The cylinders were filled, saturated with water, and drained as in the preceding year. After seepage had ceased a glass plug was placed in the one-hole rubber stopper in the bottom of each, and the cylinders moved to the greenhouse and placed in a pit which was 3 feet deep and covered with boards overlaid first with a layer of excelsior and then with one of soil. Thus the lower half of each cylinder was protected from the heat of the sun's rays and kept at a comparatively uniform temperature.

In the case of each, except the check cylinders III and IV, 10 sprouted kernels of the same Red Fife wheat used the year before were placed in the moist surface soil and one inch of dry soil added. A week later the plants were thinned to 4 in each cylinder.

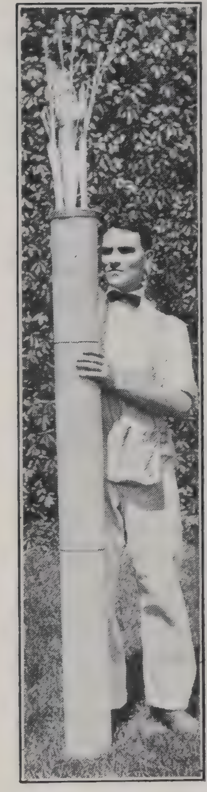

Fig. 2. One of the cylinders.

Cylinders I, II, III, and IV, with semiarid soil, were placed in the greenhouse on February 8, and the others, V, VI, VII, and VIII, with humid soil, on February 23.

Each cylinder was weighed on scales, sensitive to 15 grams, just before being placed in the pit and again on being removed at the close of the experiment.

About the middle of March all the plants became prostrated. As the windows of the greenhouse had received a coat of whitewash some ten days before this injury was first noticed, it was suspected from the experience of the preceding year that this might have been the cause. Using hydrochloric acid all the whitewash was removed from the panes (March 23). However, no marked change in the condition of the plants was observed until

April 1, after which there was a steady improvement, the plants seeming fully recovered by April 10. From this time on no whitewash was used on the windows.

Outside of the injury following the use of whitewash, conditions generally were quite favorable. No temperature record was kept. The evaporation from a free water surface in the greenhouse amounted to 12.2 inches between May 3 and July 31 (Table 2).

On account of the experience of the preceding year the appearance of a crevice around the edge of the soil column was watched for from the time of planting and was found first on April 17. Altho the crevice could not be seen at the top of the mulch of dry soil, it could be detected by means of a long thin spatula pressed down at the edge of the cylinder. By means of this spatula the crevice was filled with surface soil. From that time on at intervals of a few days, all the cylinders were examined for crevices and these, whenever found, were filled with surface soil, from one inch to two inches of loose dry soil being kept as a mulch on the surface of each cylinder. No crevices developed in either of the unplanted cylinders III and VI, but sooner or later they appeared in each of the others. Later, when the cylinders were opened, the exact extent of these crevices was determined.

By May 25 a hard crust had developed at a depth of from 1.0 to 1.5 inches below the surface in I, II, IV, and VII. Later it developed in V and VIII also, but not in the unplanted cylinders, III and VI.

On March 13 the numbers of the tillers in I, II, and IV were 9, 8, and 9 respectively. In order to determine the effect upon the soil moisture that would be produced by reducing the stand, two plants containing 0.439 grams dry matter were removed from II on March 22; on April 24, the four plants in II having 23 tillers, 19 of these, containing 1.16 grams dry matter, were removed, leaving two plants with 2 tillers each. On the latter date the four plants in I had 27 tillers and the four plants in IV had 31. The average height of the plants in I, II, and III was 12, 12, and 12.5 inches, respectively. The plants on eastern Nebraska soil had made much less growth than those on western Nebraska soil, having only 0, 3, and 3 tillers and being only 9, 9.5, and 12 inches high respectively on April 24. Altho thruout the experiment the plants on humid soil made less growth, they were quite as healthy in appearance. Not until near the end of May did the thinning of the plants in II cause them to show any advantage over those in I and IV, but during the final month of their growth they appeared much more vigorous and they produced better filled spikes (Table 6). Nearly all the spikes appeared during the latter part of May. On June 24 ripe heads were removed from IV and V. By July 4 all the heads were ripe except one on a late tiller in VII, which did not ripen until July 26.

The appearance of the eight cylinders on June 24 is shown in figure 3.[1]

Each culm was cut off even with the surface and removed from the cylinder as soon as it was quite dry.

The cylinders which had borne no plants were removed from the pit on June 24, weighed, and opened. The others were similarly treated as soon as possible after all the plants in them had ripened. In the case of three cylinders there was an interval of six days between the death (and removal) of the last plant and the opening of the cylinder. The presence of any crevice beside the cylinder wall, referred to above, was recorded at the time of opening the cylinder. Each section, as removed, was carefully examined for roots and well mixed before taking the sample.

No crevice was found along the walls in III and VI. In II, V, and VIII a crevice extended to 6 inches, in VII to 18, in I to 39, and in IV to 66 inches. Where the crevices did not extend below twelve inches they were found to have been completely filled with the dry surface soil, which had been worked down into them by means of the spatula, but where they extended to a greater depth they were found to have been only partly filled below the twelfth inch, leaving the portion below as an intercommunicating air space. In IV, separate samples for moisture determinations were taken from the outer and from the inner portion of the soil column in the case of the four sections of the second foot. No difference in moisture content was found, indicating that no loss of moisture had taken place thru the crevice. The explanation of this is that the air in the crevice had been kept in a saturated condition, it being in contact with soil which contained not less than the maximum amount of hygroscopic moisture.

Roots were numerous in the first foot in all the cylinders bearing plants. In I and IV they were numerous and well distributed at all depths to the bottom of the cylinder; in II they penetrated as deeply but were not as numerous, while in V, VII, and VIII they were very scarce below 24, 21, and 21 inches respectively, but a few were found to extend to 39, 45, and 60 inches respectively. As no attempt was made at a quantitative separation of the roots from the soil, some may have been over-

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[1] Alway, F. J. Moisture Studies of Semiarid Soils. Report of Winnipeg meeting of the British Association for the Advancement of Science, 1909, p. 699. Photograph reproduced in Widtsoe's "Dry Farming," 1911, p. 96.

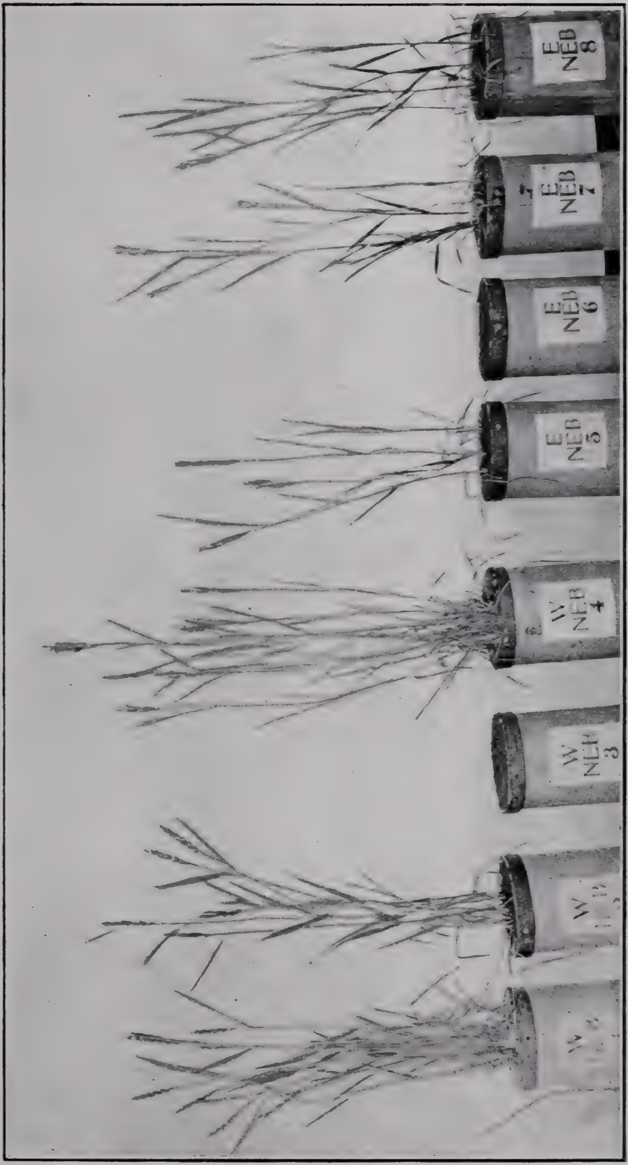

Fig. 3. Experiment of 1909, 136 days after planting in western Nebraska soil and 121 days after planting in eastern Nebraska soil.

looked, the soil in the lower portion of all the cylinders being very wet and sticky.

The stopper of III was removed and the cylinder left in a vertical position for 16 hours before opening, but no seepage occurred. In the case of VIII the nipple carrying the rubber stopper was found to have been broken off in placing the cylinder in the pit. Accordingly, the half inch opening had remained only partly closed by the rough board on which the cylinder rested; yet the soil was as moist as that in VII. From the conduct of these two cylinders it appears probable that no loss of water by seepage would have taken place even if the glass plugs had been left out of the stoppers thruout the experiment.

The data on the experiment are summarized in Table 6, and the moisture conditions at the time of opening the cylinders, and hence at the time the wheat plants died, are shown in Tables 7 and 8. Figures 4 and 5 show the relation of the final water content of the different cylinders to the hygroscopic coefficient, to the wilting coefficient, and to the initial water content of the soil. The initial water content shown in the figures is the average for the six feet and does not at all indicate the initial water content of the individual foot sections, this not being known. The initial moisture content varied a little from cylinder to cylinder and accordingly on the figures "the initial water content" as shown is not accurate for any one cylinder but is approximately correct for all four.

The soils in the check cylinders III and VI, even at the close of the experiment, after having lost about 7 and 3.5 per cent water, were wetter than such soils are found under field conditions on uplands, even where conditions have been most favorable for saturating the soil and subsoil. Thus the soil in the lower two feet of III carried about twice as much water as would have been found in the field. This large amount of water present at the beginning had permitted a continuous upward movement of water thruout the experiment, there still being a considerable amount of free water even in the second and third inch sections.

In the case of the three cylinders of eastern Nebraska soil which bore plants, nothing striking is to be observed. The moisture content increased from the surface downward. In the first foot it had been reduced below the hygroscopic coefficient, being lowest in VII on which the crop had been harvested last. The statement of the free water is no more striking than that of the total water. The dryness of the surface foot is to be attributed to direct evaporation. The data on these three cylinders furnish no evidence of the ability of the roots of the maturing wheat to reduce the soil moisture below the wilting coefficient.

TABLE 6.—*Data on experiment with Red Fife wheat in 1909.*

	Western Nebraska				Eastern Nebraska			
	III	II	I	IV	VI	V	VII	VIII
Number of plants in cylinder	0	2	4	4	0	4	4	4
Weight of dry soil in cylinder, in grams	37,960	38,056	38,153	37,960	36,990	36,606	36,700	36,312
Weight of water in soil at planting time, in grams	12,928	13,029	13,077	12,825	12,841	12,719	12,582	12,963
Weight of water in soil on opening cylinder, in grams	10,123	5,574	5,841	3,553	11,404	9,730	8,980	9,139
Weight of water lost	2,805	7,455	9,236	9,272	1,437	2.989	3,602	3,824
Time from planting seed to death of last plant, in days	......	142	142	140	......	127	153	131
Average height of plants at maturity, in inches	....	22.7	20.3	24.0	......	16.5	15.3	19.8
Number of spikes	.....	6	12	11	......	4	5	4
Number of grains	.....	111	122	182	...	35	34	45
Weight of grains, air-dry, in grams	......	3.30	3.74	5.14	......	0.83	0.88	1.29
Weight of crop dried at 110° C., in grams	....	11.0	16.4	17.9	.....	3.2	4.3	5.4
Weight of water lost per gram of crop, in grams	.....	678	563	518	.....	934	838	708
Date of death of last plant	......	June 30	June 30	June 28	......	June 30	July 26	July 4
Date of opening cylinder	June 24	July 6	July 6	June 28	June 24	July 6	July 26	July 6
Per cent of total water in soil of cylinder, on planting seed	34.1	34.2	34.3	33.8	34.7	35.5	34.4	35.5
Per cent of total water in surface foot on opening cylinder	19.8	6.2	6.5	5.6	22.0	8.2	5.9	8.2
Per cent of free water in surface foot on opening cylinder	10.8	—2.3	—2.1	—2.6	12.0	- 1.8	—4.1	—1.6
Per cent of total water in 2-6 ft. on opening cylinder	28.5	15.3	10.0	9.4	33.7	30.5	27.7	28.5
Per cent of free water in 2-6 ft. on opening cylinder	19.9	6.7	1.4	0.8	20.1	17.2	14.5	15.2

TABLE 7.—*Moisture conditions at opening of cylinders of humid soil, experiment of 1909.*

Depth of section		Total water				Hygroscopic coefficient	Free water			
		VI	V	VII	VIII		VI	V	VII	VIII
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	1	6.9	3.6	3.2	4.0	9.6	—2.7	- 6.0	—6.4	—5.6
	2-3	17.1				9.6	7.5			
	4-6	23.1	7.4	4.8	6.1	10.1	13.0	—2.7	- 5.3	—4.0
	7-9	25.0	9.7	6.6	9.8	10.1	14.9	- 0.4	—3.5	.3
	10-12	26.1	12.1	9.0	13.1	10.4	15.7	1.7	- 1.4	2.7
2	13-15	27.8	16.4	15.8	15.7	11.6	16.2	4.8	4.2	4.1
	16-18	28.7	19.3	18.2	18.6	11.6	17.1	7.7	6.6	7.0
	19-21	29.4	21.3	19.5	19.3	11.6	17.8	9.7	7.9	7.7
	22-24	29.6	23.9	21.9	20.9	11.6	18.0	12.3	10.3	9.3
3	25-27	31.8	28.2	24.5	24.5	15.1	16.7	13.1	9.4	9.4
	28-30	31.6	29.7	25.1	26.5	15.1	16.5	14.6	10.0	11.4
	31-33	33.3	30.3	28.8	28.2	15.1	18.2	15.2	13.6	13.1
	34-36	32.4	30.3	28.5	28.8	15.1	17.3	15.2	13.4	13.7
4	37-39	32.1	30.2	28.0	28.6	13.9	18.2	16.1	14.1	15.7
	40-42	32.9	31.0	28.8	29.5	13.9	19.0	17.1	14.9	14.6
	43-45	32.9	32.1	30.0	31.5	13.9	19.0	18.2	16.1	17.6
	46-48	34.5	32.2	29.9	32.6	13.9	20.6	18.3	16.0	18.7
5	49-51	36.4	34.9	32.2	33.1	13.6	22.8	21.3	18.6	19.5
	52-54	36.3	34.0	31.0	31.9	13.6	22.7	20.4	17.4	18.3
	55-57	36.0	35.0	30.2	31.9	13.6	22.4	21.4	16.6	18.3
	58-60	36.8	37.1	31.7	32.9	13.6	23.2	23.5	18.1	19.3
6	61-63	37.3	37.1	32.6	34.2	12.5	24.8	24.6	20.1	21.7
	64-66	38.7	36.4	32.7	34.2	12.5	26.2	23.9	20.2	21.7
	67-69	38.1	36.4	33.3	34.2	12.5	25.6	23.9	20.8	21.7
	70-71	37.9	35.6	31.7	34.0	12.5	25.4	23.1	19.2	21.5
Average	1-12	22.0	8.2	5.9	8.2	. . . . . .	12.0	- 1.8	—4.1	—1.6
Average	13-71	33.7	30.5	27.7	28.5	. . . . . .	20.4	17.2	14.5	15.2

TABLE 8.—*Moisture conditions at opening of cylinders of semiarid soils, experiment of 1909.*

Depth of section		Total water				Hygroscopic coefficient	Free water			
		III	II	I	IV		III	II	I	IV
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*	*Per cent*
1.	1	7.9	3.7	4.3	3.3	8.5	-0.6	—4.8	—4.2	—5.2
	2-3	16.7					8.2			
	4-6	20.5	5.1	6.0	4.4	8.4	12.1	—3.3	—2.4	-4.0
	7-9	21.2	6.9	6.6	7.4	8.5	12.7	—1.6	—1.9	—1.1
	10-12	21.7	9.0	8.5	8.4	8.6	13.1	0.4	—0.1	—0.2
2.	13-15	22.0	11.8	10.1	10.0	8.8	13.2	3.0	1.3	1.2
	16-18	22.6	11.9	10.4	10.0	8.8	13.8	3.1	1.6	1.2
	19-21	24.1	12.7	10.7	9.8	8.8	15.3	3.9	1.9	1.0
	22-24	26.5	14.4	10.8	9.9	8.8	17.7	5.6	2.0	1.1
3.	25-27	28.0	14.9	12.1	11.7	10.4	17.6	4.5	1.7	1.3
	28-30	27.6	15.3	12.1	11.6	10.4	17.2	4.9	1.7	1.2
	31-33	27.7	16.1	12.3	11.8	10.4	17.3	5.7	1.9	1.4
	34-36	28.0	16.2	11.9	11.6	10.4	17.6	5.8	1.5	1.2
4	37-39	28.0	16.3	10.4	10.1	9.3	18.7	7.0	1.1	0.8
	40-42	27.8	17.0	10.8	10.3	9.3	18.5	7.7	1.5	1.0
	43-45	28.5	16.9	10.4	10.2	9.3	19.2	7.6	1.1	1.0
	46-48	28.2	17.0	9.5	9.2	9.3	18.9	7.7	0.2	—0.1
5.	49-51	29.3	15.7	9.1	7.7	7.4	21.9	8.3	1.7	0.3
	52-54	29.2	15.3	8.9	7.6	7.4	21.8	7.9	1.5	0.2
	55-57	29.3	15.3	8.7	7.6	7.4	21.9	7.9	1.3	0.2
	58-60	32.4	15.4	8.4	7.7	7.4	25.0	8.0	1.0	0.3
6	61-63	32.2	15.3	8.2	7.6	7.1	25.1	8.2	1.1	0.5
	64-66	32.6	15.7	8.2	8.0	7.1	25.5	8.6	1.1	0.9
	67-69	33.5	15.8	8.4	7.9	7.1	26.4	8.7	1.3	0.8
	70-71	31.6	15.8	7.6	7.4	7.1	24.5	8.7	0.5	0.3
Average	1-12	19.8	6.2	6.3	5.9	. . . .	10.8	—2.3	-2.1	—2.6
Average	13-71	28.5	15.3	10.0	9.4	. . . .	19.9	6.7	1.4	0.8

Very different from the above are the data on the three cylinders of semiarid soil. In the first foot alone were the conditions similar to those in the three cylinders of humid soil, the drying due to direct evaporation having extended to the bottom of the surface foot. Below the first foot conditions were very different. There was no regular rise in moisture content with increasing depth, it rising and falling independently of the depth. The moisture in the four 3-inch sections of each foot was uniform within the limits of experimental error. Here the statement of the free water is instructive. In I and IV, which had produced the heaviest crops, the moisture in the different foot sections below the surface foot had been reduced almost to the hygroscopic coefficient, viz, to 1.4 per cent of free water in I and to 0.8 per cent in IV. In II, which had not produced as heavy a crop, the moisture content was considerably (6.7 per cent) above the hygroscopic coefficient and the moisture rose slightly from the surface downward. In all three the roots had penetrated freely to the very bottom of the cylinders, being found even in the sand layer. When the soil moisture had run low the roots seem to have drawn quite uniformly on the free water in the different levels.

The data given on line 12 of Table 6 on the loss of water per gram of dry matter of crop produced include the water lost by direct evaporation from the soil as well as that transpired. A satisfactory correction for the amount lost by direct evaporation cannot be made from the data on hand. It is certainly considerably below that lost from the unplanted cylinders. The great difference between the two unplanted cylinders is to be attributed, at least in part, to the marked difference in water capacity of the soils they contained, while the initial total moisture content was very similar in both. The water transpired per unit of dry matter produced lies between the very wide limits of 518 and 934. The yields of grain calculated to an acre basis are interesting, those on the semiarid soil being 26, 30, and 41 bushels and on the humid soil 6, 7, and 10 bushels. Such a result could not be obtained in the field on a deep, well-drained semiarid soil similar to that used, unless water were added during the growth of the crop, for the reason that so much water would not be held in the surface six feet.[1]

On the H O Ranch, 200 yards from where the semiarid soil was obtained, there was a young orchard which had been kept in clean cultivation for 3 years. On November 21, 1907, the soil con-

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[1] It should be emphasized in this connection that 6 feet is not the limit of root penetration for wheat on all semiarid soils where free water in considerable quantity extends to a greater depth.

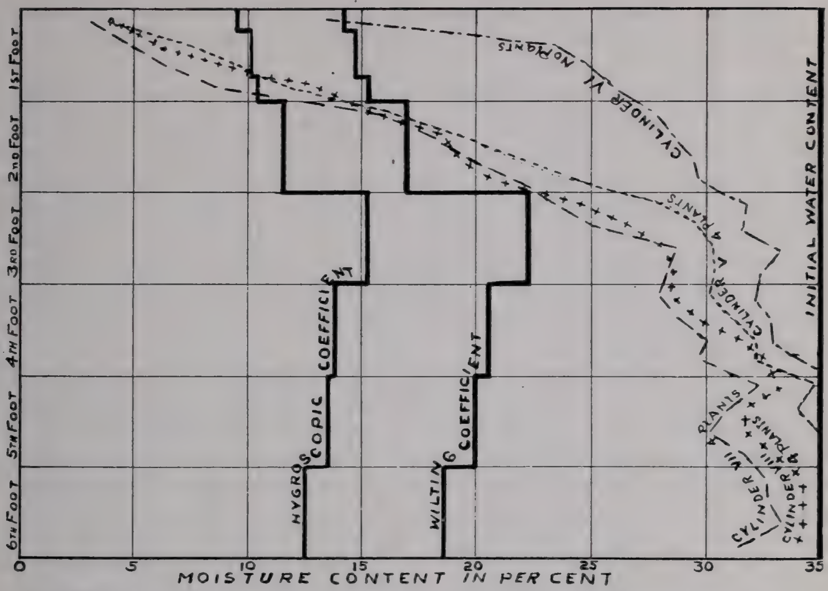

Fig. 4. Final moisture conditions in cylinders of humid soil.

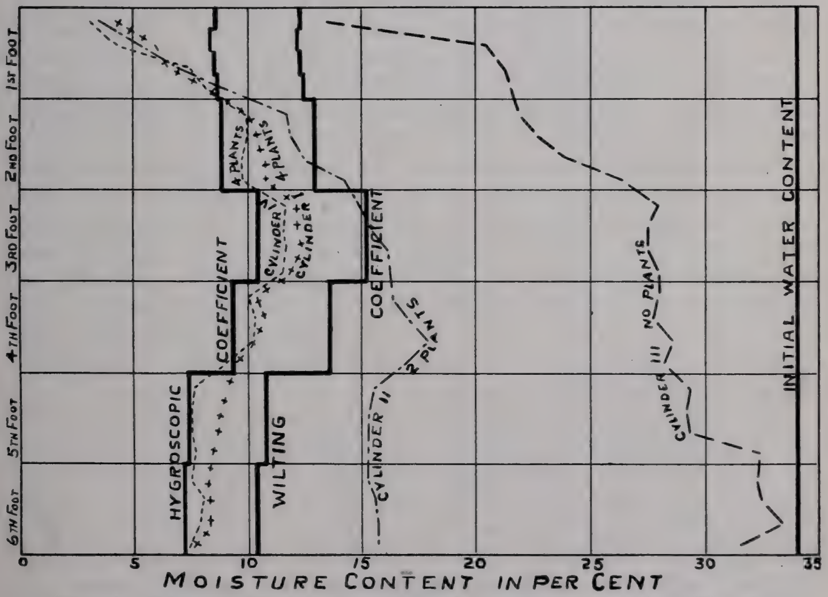

Fig. 5. Final moisture conditions in cylinders of semiarid soil.

tained an average of 17.8 per cent total water and had a hygroscopic coefficient of 7.6. In the adjacent prairie a shallow pit, 12 feet in diameter, was dug on November 9, 1907. During the following four days 28 inches of water was added. Ten days later the first six feet contained 21.1 per cent total water and at the end of the following April, the surface having been protected from evaporation in the interval, it contained 17.3 per cent total water —much the same as the soil of the adjacent orchard. Thus the same depth of soil in the cylinders with a quite similar hygroscopic coefficient, averaging 8.5, contained about 25 per cent free water while similar soil in the field, both when saturated by fallowing and when saturated by irrigation, contained only about 10 per cent free water.

On the Experiment Station farm, part of a young orchard had been kept in clean cultivation for ten years. In the most moist soil that was found in this field the total water in the first 6 feet was 26.1 per cent, with an average hygroscopic coefficient of 11.9, while the humid soil in the cylinders contained about 35 per cent total water and had an average hygroscopic coefficient of 12.8.

Summary of experiment.—At the time the seeds were planted the cylinders of semiarid soil carried more than twice as much water as the same soil would have retained under field conditions, while the cylinders of humid soil carried at least one-fourth more than the same soil in the field would have retained. The loss of water—wholly by direct evaporation—from the two unplanted cylinders during the four months of the experiment was equivalent to about 5.0 inches of rainfall in the case of the semiarid soil and to 2.5 inches in that of the humid soil. Normal plants were produced on both soils and the yields of grain, calculated to an acre basis, exceeded 25 bushels on the semiarid soil but were less than 11 bushels on the humid soil, the former being much higher than could be expected from the same depth of subsoil under field conditions, because of the excessive quantity of free water at the time of planting. In no case, however, was the proportion of grain to straw or the loss of soil water per unit weight of dry matter produced more favorable than might be expected in the field.

The plants on the semiarid soil made a much greater growth and rooted much more deeply. They also made a more economical use of the soil water than did those on the humid soil; however, this economy may have been due entirely to a smaller evaporation from the cylinders of semiarid soil. After the plants had matured there was a marked difference between the semiarid and the humid soil in the moisture condition of the subsoil but not in that of the surface foot. The transpiration of water from the semiarid soil was lowered by reducing the foliage of the plants, but the depth of penetration of the roots was not thereby lessened.

The final water content of the humid subsoil in this experiment bore no relation to either the wilting coefficient or the hygroscopic coefficient. In the two cylinders of semiarid soil in which there was barely enough water to mature seed there was a direct dependence of the final water content upon the hygroscopic coefficient, the former being only a little above the latter. In the semiarid subsoil in which roots were well developed, the final content of free water was independent of the distance of the subsoil from the surface, except in one cylinder, and in this there remained an abundance of free water even after the death of the plants. In the latter the free water content increased slightly with the distance from the surface.

In all 6 of the cylinders which bore plants a hard crust developed under the surface mulch but appeared to have no injurious effect on the plants.

GROWTH OF CROP PLANTS WITH DIFFERENT AMOUNTS OF WATER IN THE SUBSOIL. EXPERIMENT OF 1910.

The 22 metal cylinders used in this experiment were of the same material, form, and dimensions as those employed in 1909. After being filled, 2 were left unplanted, 6 were planted to Red Fife wheat, 6 to Kubanka wheat, 6 to milo, and 2 to Mexican pink beans. The 20 were planted on February 5, the two unplanted cylinders like the others being provided with a one-inch mulch of dry soil. All the cylinders, as soon as the mulch of air-dry soil had been added, were removed to the greenhouse and sunken in a rectangular pit four feet deep. The portions above the surface were enclosed by planks and banked up with soil as shown in figure 6, thus protecting all but the surface 3 to 6 inches from the heat of the direct rays of the sun and the rapidly varying air temperatures. (When the photograph was taken some of the soil was removed from the sides so as to show the numbers on the cylinders.)

Beginning near the middle of March a record was kept of the daily maximum and minimum temperatures and of the evaporation from a free water surface. A little later a record of the humidity was begun. While the humidity did not differ much from that in the open air, the maximum daily temperature on more than half the days exceeded 100° F. and the experiment was finally cut short by a temperature of 124° F. on June 12. (Table 4.)

This temperature in itself would not have been fatal to the plants had the soil moisture not already been reduced to such a low point. Sixteen pots with maize plants from 3 to 4 feet high in the same greenhouse and only a few feet from the cylinders thruout the day remained uninjured but they had been liberally watered early in the morning of June 12.

No whitewash was used on the windows of the greenhouse.

As in the experiment of the preceding year, a close watch was kept for the development of any crevice between soil column and cylinder wall, and as soon as one appeared loose surface soil was at once worked down into it. Later, when the cylinders were opened, it was found that no crevices had extended below twelve inches, and all were full of surface soil. Accordingly there had been no opportunity for direct evaporation from the sides of the soil columns. In order to maintain a good mulch in some of the cylinders, it was necessary, on account of a portion of the original mulch having been worked down into these crevices, to add more dry surface soil, amounting to from 300 to 500 grams, the amounts being recorded at the time and included in the totals given in Tables 11, 13, 15, and 17.

No soil crust formed below the mulch in the unplanted cylinders but in all the others a very hard crust had developed by the end of the second month after planting.

As soon as the plants in a cylinder died they were removed, the cylinder opened as soon as convenient and the moisture of the soil determined. The roots in the different foot sections of the subsoil were separated out, photographed, dried, and weighed.

The experiments were much simpler in so far as the soils were concerned than those of the preceding year. Only semiarid soil, again from the H O Ranch, was used and this consisted of only three bulk lots, namely, the first 6 inches, the second 6 inches, and a composite subsoil referred to hereafter as "H O Subsoil." The last was taken from the fourth, fifth, and sixth feet in an excavation made in the prairie field from which the soils used in 1908 and 1909 had been secured. After this subsoil reached the Experiment Station it was thoroly mixed, while dry, by shoveling, passed thru an eighth-inch screen, and again mixed. This subsoil was not only representative of the subsoils of an important dry land area of the state but it was such that it could be placed in the cylinders so as to be very similar to the condition in which it occurs naturally. Extensive studies of this soil in pits and borings on the H O Ranch, as well as in various other cylinder experiments, have shown that there is a very close resemblance between the condition of the soil, both in the wet and in the dry state, in cylinders and the condition of it in the field.[1]

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[1] A fuller description of the properties of the "H O Subsoil" is given on p. 249 of the article by Alway and Clark, referred to on p. 28.

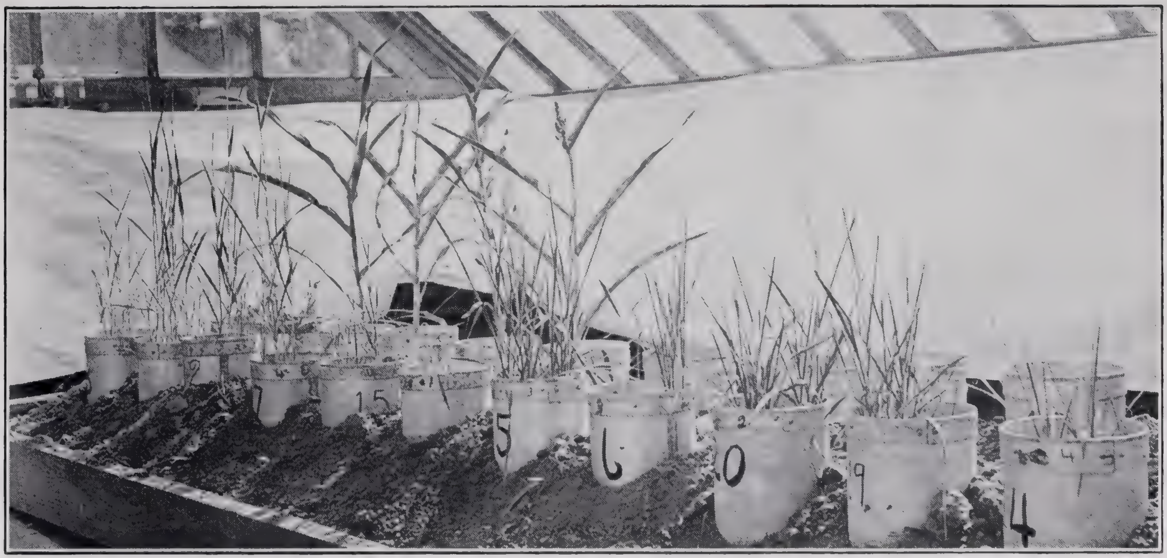


Fig. 6. Experiment of 1910, 96 days after planting seed.

As only three different soils were used in the 22 cylinders and as these had been thoroly mixed, the determination of the hygroscopic coefficients was a simple matter. The most interest attaches to the subsoil and of this a very large number of determinations were made, the average being 5.6. The values for the first 6-inch and the second 6-inch samples are 9.3 and 11.0 respectively.

FILLING THE CYLINDERS.

In all the 22 cylinders when filled there were only three different soils, the soil below the first foot being uniform, except for a layer of coarse sand weighing 400 grams and about three-fourths of an inch in thickness, which was placed in the bottom of each cylinder in order to facilitate drainage.

The method of applying water used in 1908 and 1909 was not employed in this experiment for the reason that it left in the soil after seepage had ceased so very much more water than the same soil under dry-land field conditions would carry. Ten of the cylinders were filled with air-dry soil, after which enough water was added to give the desired total amount. The other 12 were filled with moist subsoil, water being added, after the filling, only to moisten the surface foot. Germinated seeds were planted in all but 2 of the cylinders on the same day, these 2 being left unplanted.

Ten, I to X, were filled with dry soil in much the same way as in 1909, all except the surface inch being added with tamping. The weight of each of the three kinds of soil used for each cylinder, as well as the percentage of moisture in each, was determined and from these data there was calculated the amount of water contained in the air-dry soil of each cylinder; then enough water was added to each to make the total amount present equal to 25 per cent of the dry weight of the surface foot and 18 per cent of the dry weight of the subsoil. During the adding of the water, which lasted over several days, the tops of the cylinders were kept covered to prevent evaporation and the glass plugs were removed from the one-hole rubber stoppers. As soon as all the added water had soaked into the soil, the glass plugs were returned, the cylinders were weighed and placed in the pit in the greenhouse, germinated seeds were planted one inch deep in the moist soil, and the final inch of dry surface soil added. No seepage had occurred in the case of any of these before the plugs were inserted and doubtless none would have occurred if the plugs had been left out.

For the 12 cylinders in which the subsoil was moistened before being placed in the cylinder, eight lots of prepared subsoil were used. Each lot of moist subsoil was prepared by placing a weighed quantity of the air-dry soil, of which the moisture content had been determined, on a smooth cement floor and adding the calculated amount of water in small portions while the mass was being shoveled over. The whole was mixed thoroly, first by shoveling, then by passing it twice thru a swinging sieve of one-fourth-inch mesh, and finally by again shoveling the mass thoroly. The moist soil thus prepared was immediately placed in a large covered can in which it was kept until transferred to the cylinders. The moisture percentages reported in the tables are those actually found in the soil after it had been mixed and placed in the large cans; thus, for example, where it was desired to obtain a series of moist subsoils containing 6.0, 10.0, 14.0, and 18.0 per cent of water, there was obtained instead a series with 5.8, 9.8, 14.1, and 18.2 per cent respectively.

Solid instead of one-hole rubber stoppers were placed in the drainage nipples of these 12 cylinders before the filling was begun. A small amount of the subsoil was added at a time and tamped before adding more. When a cylinder was filled to within twelve inches of the top all of the second 6-inch bulk sample, and also all of the first 6-inch bulk sample, except the final inch, was added with constant tamping. The two portions of the surface foot were added in an air-dry condition. Then using the method described on page 48 there was added the amount of water required to raise the total moisture content of the surface foot to 20 per cent. When the water had soaked away the cylinders were placed in the pit in the greenhouse, the seed planted, and the final inch of air-dry soil added.

SEPARATION OF ROOTS FROM THE SUBSOIL.

As the subsoil was very dry in most of the cylinders, it was easy to screen out the roots. In the case of each 3-inch section, after a pint sample, to be used for the moisture determination, had been placed in a jar, the rest was passed thru an eighth-inch screen. The portion of the section placed in the jar was not thus screened, but as it was being transferred to the jar a careful watch for roots was maintained. Where the soil was too moist to pass readily thru the screen, as in the lower part of cylinder VIII, it was allowed to stand in a jar of water for a few hours and then washed thru the screen, using a jet of water. All the roots thus secured from the four 3-inch sections of each foot were placed in a jar of 2 per cent formaldehyde and left until all the cylinders had been opened. Finally the roots were washed on a screen in running water, carefully separated from other organic residues, placed on disks of black filter paper, and photographed. Then they were dried and weighed. No attempt was made to separate the roots from the surface foot of soil. As among the notes on each 3-inch section, recorded at the time of opening the cylinders, mention was always made of the relative abundance of roots, there are three checks on the relative root development in each foot section, viz, these notes, the photographs, and the weight of dry matter in the roots. In a few instances where the presence of a very few fine roots was recorded in the notes, the roots were lost in the subsequent operations before the photographs were taken. As previous to the filling of the cylinders the subsoil had all been passed thru an eighth-inch screen, nearly all the old roots had thus been removed. However, before photographing them the root fragments from the different foot sections were gone over with forceps, handling them one by one and rejecting all that did not appear fresh.

While, for the purpose of securing photographs of the roots, it would have been desirable to leave them intact and attached to the plant, such was not feasible in this experiment, which was designed especially to secure accurate data on the distribution of the soil moisture in short sections, the determination of the quantitative distribution of the roots being a secondary consideration.

TABLE 9.—*Cylinders used in 1910 experiment.*

Cylinder No.	Crop	Free water at time of planting		Date of death of last plant	Date of opening cylinder
		Surface foot	Subsoil 2 to 6 ft.		
		Per cent	*Per cent*		
I	Mexican beans. . .	14.9	12.4	May 13	May 13
II	Mexican beans. . .	14.9	12.4	May 13	May 13
III	Milo.	14.9	12.4	May 13*	May 13
IV	Milo	14.9	12.4	June 14	June 14
V	Red Fife wheat	14.9	12.4	June 14	June 14
VI	Red Fife wheat . .	14.9	12.4	June 14	June 14
VII	Kubanka wheat. .	14.9	12.4	June 14	June 14
VIII	Kubanka wheat. .	14.9	12.4	June 14	June 14
IX	No crop.	14.9	12.4	. . . . . .	May 13
X	No crop.	14.9	12.4	. . . .	May 13
XI	Kubanka wheat. .	9.9	0.2	May 9	May 13
XII	Milo	9.9	0.2	May 13	May 13
XIII	Red Fife wheat. .	9.9	0.2	May 9	May 13
XIV	Red Fife wheat. .	9.9	4.2	June 14	June 14
XV	Kubanka wheat. .	9.9	4.2	June 14	June 14
XVI	Milo	9.9	4.2	June 14	June 14
XVII	Kubanka wheat. .	9.9	7.8	June 14	June 14
XVIII	Milo.	9.9	8.5	June 14	June 21
XIX	Red Fife wheat .	9.9	7.4	June 14	June 21
XX	Red Fife wheat. .	9.9	11.5	June 14	June 21
XXI	Milo	9.9	12.6	June 14	June 21
XXII	Kubanka wheat. .	9.9	12.2	June 14	June 14

* Plant not quite dead when removed.

Table 9 gives a summary of the initial moisture conditions in the different cylinders, of the crops grown, and of the dates of harvesting the crops and opening the cylinders.

CYLINDERS WITHOUT PLANTS.

These were left undisturbed from the time that they were placed in the greenhouse until they were removed from the pit and opened, except from time to time to examine them by means of a spatula for the formation of a crevice along the cylinder wall and to test them by means of a sharp pointed stick, for the presence of a crust under the surface mulch. No crevice formed and no hard crust was found, altho when the cylinders were opened on May 13 a crust was beginning to form in each.

As shown in Table 10, the percentage of total moisture increased steadily from the surface to the bottom of the first foot, where there was a sudden drop from 22 per cent to 13 per cent. From this point on down it increased steadily to the bottom of the subsoil, where it reached 21 per cent. There was practically the same moisture content at corresponding depths in the two cylinders. The surface foot was much drier than in the experiment in 1909 and much less water had been lost by evaporation.

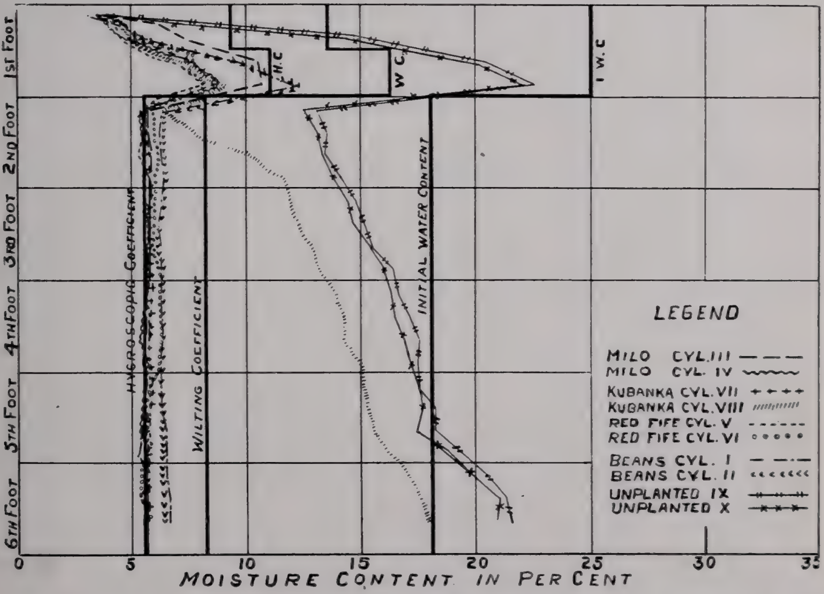


Fig. 7. Final moisture conditions in ten cylinders with the moistest surface soil.

While the amount of added water had not been enough to cause it to seep from the bottom of the cylinder, it was enough to have supersaturated the soil if it had been under field conditions. The moisture relations are shown in figure 7.

RED FIFE WHEAT.

The seed used was from one of the plants grown on semiarid soil in the experiment of 1909. Ten seeds were planted in each of the 6 cylinders on February 5; 23 days later, when the plants were from 4 to 12 inches high, they were thinned to the most vigorous 4 in each cylinder. No further thinning was practiced, except in the case of VI, from which 3 plants were removed on April 27. The thinnings were dried and the weights included in those of the total dry matter reported in Table 11. Little difference between the plants in the six cylinders was observed until the end of the first month.

A summary of the data of the experiment is given in Table 12 and the moisture conditions in the soil at the death of the plants are shown in Table 11 and in figures 7 to 11. Figure 12 shows the condition of the plants on April 23 and on June 8 respectively. The roots separated from the different foot sections of the subsoil are shown in figure 13.

TABLE 10.—*Moisture conditions on opening unplanted cylinders, experiment of 1910.*

Depth of section		Total water		Free water	
In feet	In inches	IX	X	IX	X
		Per cent	*Per cent*	*Per cent*	*Per cent*
1	1-3	3.8	3.9	—5.5	—5.4
	4	7.6	7.3	—1.7	—2.0
	5-6	14.8	14.5	5.5	5.2
	7-9	20.4	20.2	9.4	9.1
	10-12	22.5	22.0	11.5	11.0
2	13-15	13.1	12.6	7.5	7.0
	16-18	13.6	13.1	8.0	7.5
	19-21	13.5	13.4	7.9	7.8
	22-24	14.2	13.8	8.6	8.2
3	25-27	14.8	14.4	9.2	8.8
	28-30	15.1	14.7	9.5	9.1
	31-33	15.6	15.4	10.0	9.8
	34-36	16.4	16.0	10.8	10.4
4	37-39	16.7	16.3	11.1	10.7
	40-42	17.1	16.4	11.5	10.8
	43-45	17.6	16.9	12.0	11.3
	46-48	17.5	17.1	11.9	11.6
5	49-51	17.5	17.5	11.9	11.9
	52-54	18.2	17.7	12.6	12.1
	55-57	18.2	17.5	12.6	11.9
	58-60	19.3	18.7	13.7	12.1
6	61-63	20.5	19.9	14.9	14.3
	64-66	21.2	21.0	15.6	15.4
	67-69	21.5	20.9	15.9	15.3
Average	1-12	14.8	14.5	4.6	4.4
Average	13-69	16.9	16.5	11.3	10.8

	IX	X
	Grams	*Grams*
Weight of dry soil and subsoil in cylinder	43,412	42,943
Weight of water in cylinder, Feb. 5	8,216	8,102
Weight of water in cylinder, May 13	7,403	7,033
Weight of water lost in 97 days	813	1,069
Per cent of total water in surface foot of soil, Feb. 5	25.0	25.0
Per cent of total water in subsoil, Feb. 5	18.0	18.0
Per cent of total water in surface foot of soil, May 13	14.8	14.5
Per cent of total water in subsoil, May 13	17.4	16.7

TABLE 11.—*Data on experiment with Red Fife wheat in 1910.*

	V	VI	XIII	XIV	XIX	XX
Weight of dry soil and subsoil in cylinder, in grams	4 ,272	42,339	4 ,510	43,343	44, 53	46,209
Weight of water in soil and subsoil, February 5, in grams	8 076	,007	3,332	4,831	6,161	,060
Weight of water in soil and subsoil at opening of cylinder, in grams	2,377	2,492	2,543	2.976	2,681	3,237
Weight of water lost	5,699	5,515	789	1,85	3,480	4 8 3
Time from planting of seed to maturing of plant, days	129	129	93	1 9	129	129
Height of plants at the time of maximum development, in inches	15.5	12.	9.	10.	18 0	15.0
Number of spikes		0	0	1	3	4
Number of grains	0	0	0	0	3	6
Weight of grains, air-dry, in grams	0		0	0	0	.15
Weight of leaves, stems, etc., air-dry, in grams	8.2	6.8	0.6	2.0	4.8	9.1
Weight of crop dried at 110° C., in grams	7.5	6.1	0.6	1.8	4.35	8.25
Weight of water lost per gram of crop at 110° C., in grams	76	904	1315	1,031	800	584
Weight of roots, dried at 110° C., in second foot, in grams	.038	.128	.003	.018	.032	.048
Weight of roots, dried at 11 ° C., in third foot, in grams	.042	.039	.000	017	. 16	.015
Weight of roots, dried at 110° C., in fourth foot, in grams	.039	.0 5	. 00	.006	.017	.010
Weight of roots, dried at 110° C., in fifth foot, in grams	.049	. 6	. 00	.006	.015	.004
Weight of roots, dried at 110° C., in sixth foot, in grams	.068	.046	. 00	Traces	.009	Traces
Total weight of roots in subsoil	.236	.324	.003	.047	. 89	.077
Average height of plants on February 28, in inches	5.5	9.0	5.5	8.0	7.5	[illegible]
Average height of plants on March 5, in inches	9.5	11.0	9.0	9.	10.0	10.5
Average height of plants on March 12, in inches	10.5	11 5	9.	.5	11 0	11.0
Average height of plants on March 18, in inches	12.5	13.	9.5	10.0	12.0	12.0
Average height of plants on March 28, in inches	12.5	12 5	9.0*	9.5*	11.5*	12.5
Average height of plants on April 2, in inches	12.5	12.	9.0	9.5	11.	12.5
Average height of plants on April 9, in inches	14.0	12.5	8.5	9.	11.5	14.
Average height of plants on April 16, in inches	14.	1 .5	......	9.5	11.5	14.0
Average height of plants on April 23, in inches	14.5	12.0	......	[illegible]	10.0	14.5
Average height of plants on April 30, in inches	14.5	12.0	......	7.	......	14.
Average height of plants on May 7, in inches	15.0	12.5	......	7.0	9.	15.0
Date of death of last plant	June 14	June 14	May 9	June 14	June 14	June 14
Date of opening cylinder	June 14	June 14	May 13	June 14	June 21	June 1
Per cent of total water in surface foot of soil, February 5	25.0	25.0	20.0	20.0	20.0	20.0
Per cent of total water in subsoil, February 5	18.0	18.0	5.	9.8	13.0	17.1
Per cent of total water in surface foot on opening cylinder	5.8	5.8	5.8	5.8	8	6.3
Per cent of total water in subsoil on opening cylinder	5.6	5.9	6.0	6.6	6.0	7.1

* The height reported is that of the highest green point on the plant.

Table 12.—*Moisture conditions on opening cylinders with Red Fife wheat in experiment of 1910.*

Depth of section		Free water						Hygroscopic coefficient
		V	VI	XIII	XIV	XIX	XX	
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
1..........	1-3	—5.7	—5.8	—6.2	—5.4	—5.4	—6.2	9.3
	4	—5.0	—5.2	—5.6	—4.9	—5.0	—5.6	9.3
	5-6	—4.7	—4.7	—5.0	—3.5	—4.7	—4.7	9.3
	7-9	—3.9	—4.0	—4.2	—3.8	—3.7	—2.9	11.0
	10-12	—2.9	—2.6	—1.6	3.5	—3.5	—1.4	11.0
2..........	13-15	— .2	.3	— .1	— .2	— .1	.8	5.6
	16-18	— .1	.4	.2	.2	.2	.5	5.6
	19-21	— .2	.6	.5	.4	.5	1.5	5.6
	22-24	.1	.4	.6	.6	.2	1.5	5.6
3..........	25-27	.1	.4	.6	.7	.4	1.5	5.6
	28-30	.1	.4	.3	1.0	.5	1.5	5.6
	31-33	.1	.3	.2	1.1	.1	1.8	5.6
	34-36	.1	.6	.1	1.0	.5	1.5	5.6
4..........	37-39	.0	.7	.0	1.1	.4	2.0	5.6
	40-42	.1	.7	.1	1.3	.3	1.9	5.6
	43-45	.1	.7	.4	1.3	.3	2.0	5.6
	46-48	.1	.6	.3	1.2	.4	1.8	5.6
5..........	49-51	.1	.3	.3	1.5	.5	1.9	5.6
	52-54	.1	— .1	.5	1.8	.4	1.4	5.6
	55-57	.1	.1	.5	2.0	.4	1.5	5.6
	58-60	— .1	.2	.5	2.4	.4	1.5	5.6
6..........	61-63	.1	— .2	.6	2.9	.5	1.6	5.6
	64-66	— .2	— .2	.5	2.9	.5	1.5	5.6
	67-69	.1	.2	.7	3.4	.7	1.4	5.6
Average	1-12	—4.2	—4.3	—4.3	—4.1	—4.3	—3.8	10.1
Average	13-69	.0	.3	.4	1.4	.4	1.5	5.6

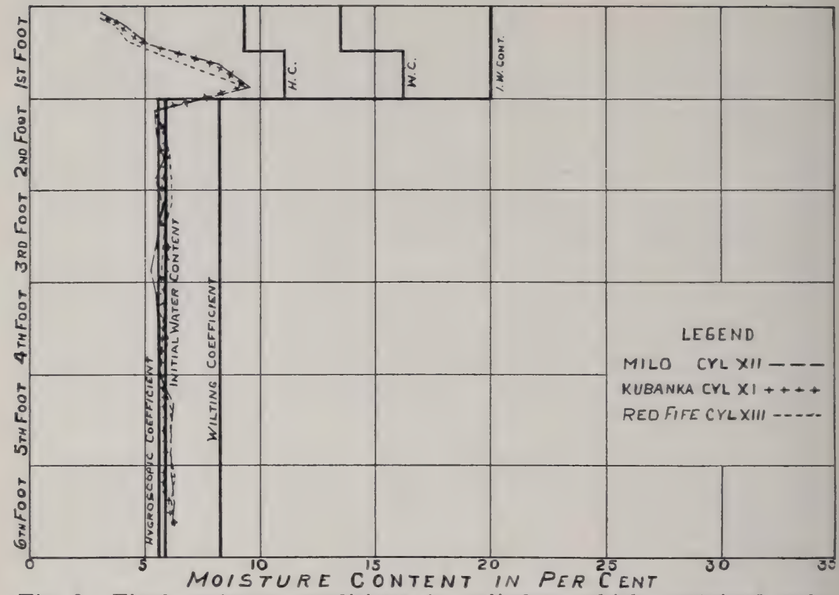


Fig. 8. Final moisture conditions in cylinders which contained only 0.2 per cent free water in the subsoil when planted.

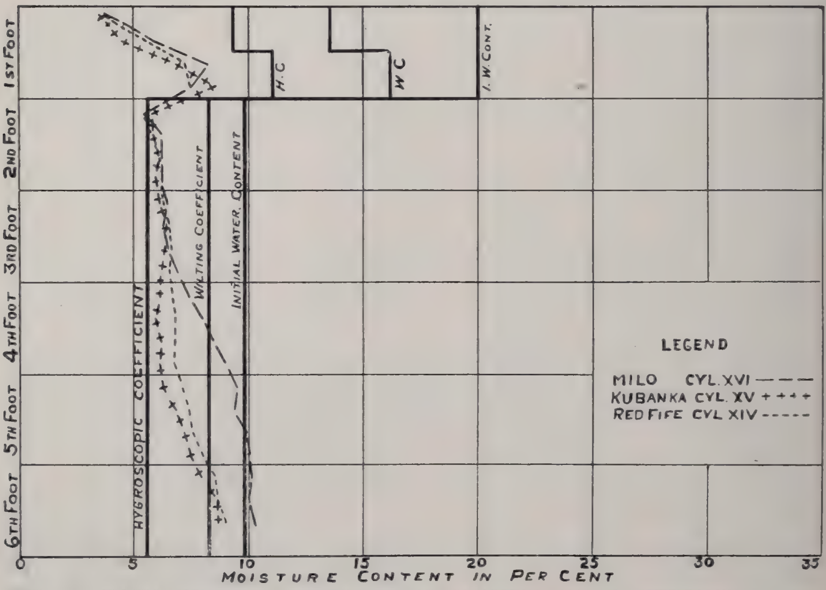


Fig. 9. Final moisture conditions in cylinders which contained 4 per cent free water in the subsoil when planted.

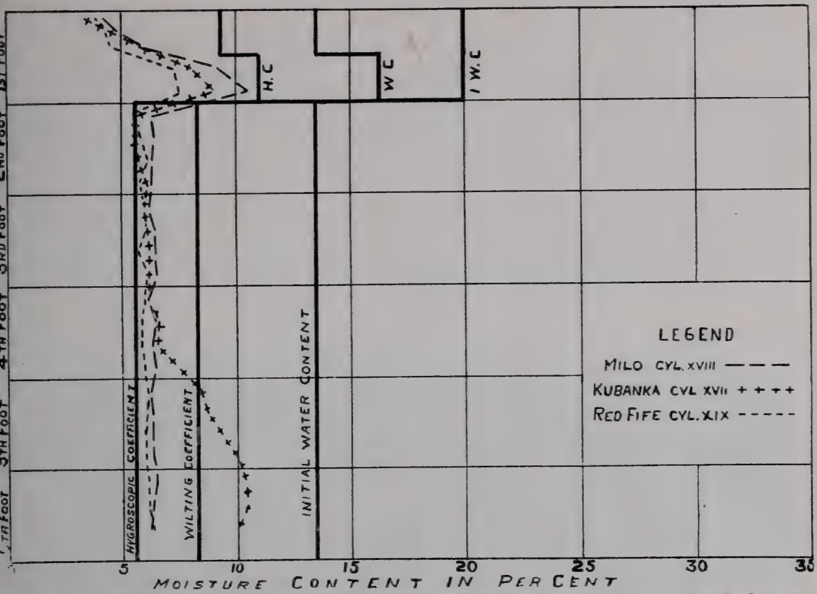


Fig. 10. Final moisture conditions in cylinders which contained 8 per cent free water in the subsoil when planted.

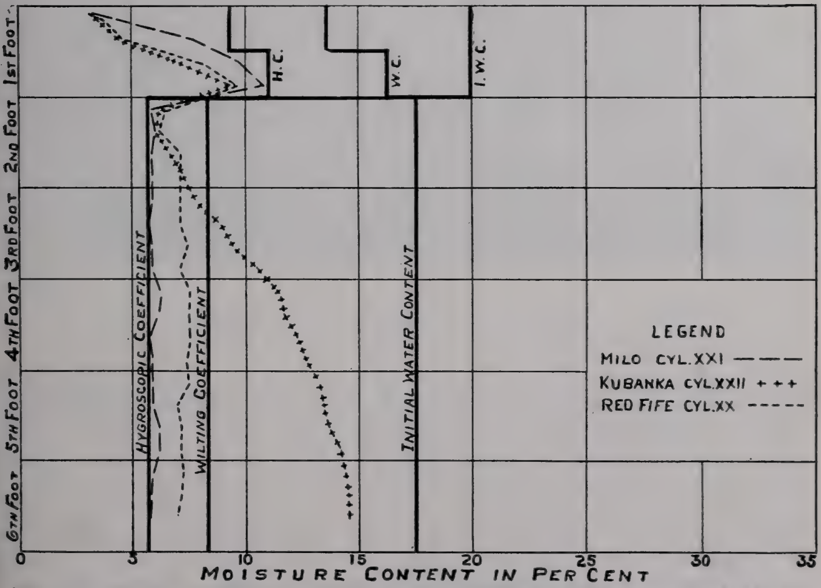
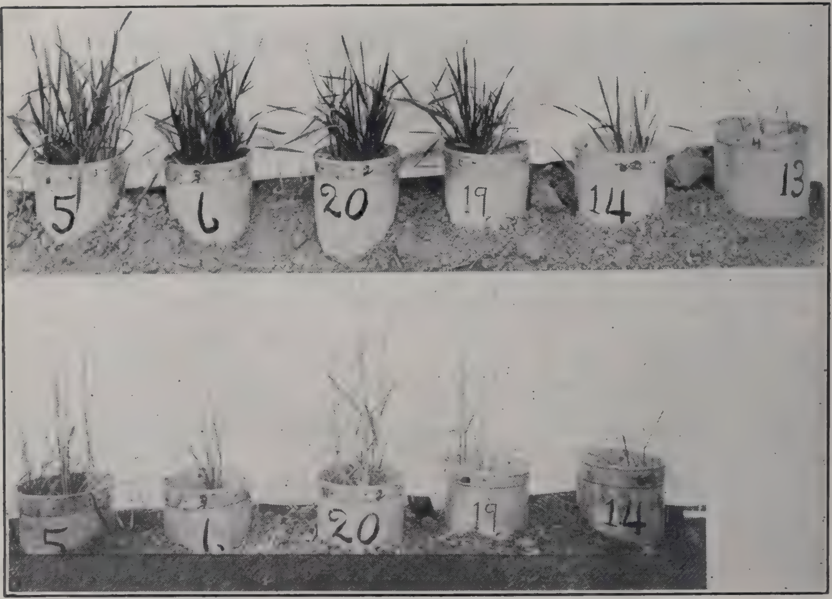


Fig. 11. Final moisture conditions in cylinders which contained 12 per cent free water in the subsoil when planted.

CYLINDER WITH NO FREE WATER IN THE SUBSOIL.—Cylinder XIII was filled with subsoil containing 5.8 per cent total water. This is practically the hygroscopic coefficient and accordingly the subsoil contained practically no free water. On the subsoil was placed eleven inches of air-dry surface soil having an average hygroscopic coefficient of 10.1 and enough water was added to raise the average percentage of total water in the surface foot to 20. Some experiments[1] carried out later indicate that practically the whole of this added water would be held within the surface twelve inches, allowing only a very little to pass by capillarity into the uppermost portion of the subsoil.



V VI XX XIX XIV XIII

Fig. 12. Red Fife wheat 77 and 123 days after planting; experiment of 1910.

The plants in this cylinder did as well as those in the five other cylinders until the fifth week, after which they rapidly fell behind. They made no growth after March 12. On March 18, after three days with high temperatures in the greenhouse, all four plants wilted and did not afterwards fully recover. None formed a tiller or put forth a spike. Their condition on April 23 is shown in figure 12. They grew steadily worse but were not entirely dead until May 13. The cylinder was opened on that date. No free water was present in the surface soil and there was practically none in the subsoil. The former contained —4.3 per cent free water and the latter 0.4 per cent. The only roots that had entered the subsoil extended about two inches below the surface foot. They are shown in figure 13. The dry matter in these roots amounted to 0.003 gram.

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[1] Analogous to those described by Alway and Clark, Twenty-fifth Annual Report of the Nebraska Experiment Station, 1912, p. 285.

The explanation of the lack of difference in growth during the first month is evident from the above. As long as the plants in all six cylinders had their roots confined to the surface foot of soil, all had about equally favorable conditions and made similar growth, but as soon as the roots were developed to the bottom of the surface foot the plants in XIII fell behind the others; the roots did not penetrate the subsoil on account of the absence in it of free water. The final dryness of the subsoil as a whole was due simply to its not having had any water to give up to the plants, while that of the surface soil was due partly to the loss thru transpiration but chiefly to direct evaporation. The increase of 0.2 per cent in the average moisture content in the five feet of subsoil may be due to a slight distillation from the moist surface soil early in the experiment, but it is probably rather to be considered within the limits of the experimental error.

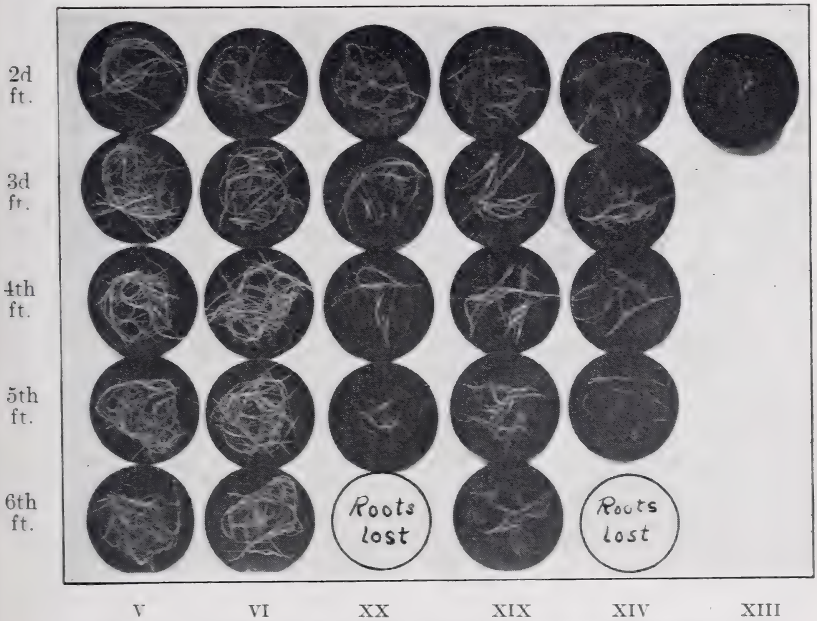

Fig. 13. Roots of Red Fife wheat; experiment of 1910.

The production of dry matter for the water lost was very low––only one part for 1315 parts of water, or the equivalent of one ton of dry matter for 11.5 inches of rain.

CYLINDERS WITH 4 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XIV was filled like XIII, except that a moist subsoil with 4.2 per cent free water was used. After the first month the plants in this did better than those in XIII, but poorer than those in any of the other cylinders. On March 18, 2 of the 4 plants wilted and did not afterwards fully recover, altho they remained alive until the middle of May. The other 2 plants did not wilt until April 3, following three days of high temperatures in the greenhouse. Both recovered and on April 30 the one plant had 2 tillers and the other 3; the latter died during the latter part of May, while the former put a spike part way out of the sheath but gave no promise of further development. It was already dying on June 11—the day before that on which the temperature in the greenhouse rose to 124° F. Two days later this plant was quite dead, having formed no grain, and the cylinder was opened. The surface foot of soil contained no free water (really —4.1 per cent) while the free water in the subsoil rose steadily from 0.0 in the upper half of the second foot to 2.1 per cent in the lower part of the sixth foot, averaging 1.4 per cent thruout the subsoil. Roots were found in all levels of the subsoil, but they were scarce in the fifth foot and only a very few small ones were found in the sixth foot. There was still an appreciable quantity of free water in the lower part of the cylinder, but the root development was not such as to permit of its rapid absorption. Except in the sixth foot the moisture content was below the wilting coefficient. It is possible that under favorable weather conditions—cool, cloudy, humid weather—or with a more extensive root development the one plant might have formed some seed. The moisture content of the subsoil was still 1.4 per cent above that of cylinder V and 1.0 per cent above that of cylinder XIX, in neither of which the last plant had yet died, but was 1.2 per cent below the wilting coefficient.

It is of interest to observe that the four plants did not all die, or even wilt, simultaneously, but that two acted independently of the other two and of one another, as tho they drew their water supply from different parts of the soil column. This is a good illustration of the difficulty of attempting in the field to decide upon the moisture content of the soil corresponding to the wilting point or to the death point. One of these four plants continued to grow and develop for some 80 days after two had permanently wilted and these two continued alive for nearly two months after so wilting.

CYLINDER WITH 7 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XIX was filled like XIII and XIV, except that moist subsoil containing 13.0 per cent total water—7.4 per cent free water—was used. All the plants did well until near the end of March, the four plants having 8 tillers on March 28. About the middle of April two of the plants began to die and were dead by June 11. The other two continued to develop until they had put three spikes part way out of the sheath. By June 8 they had ceased to grow but were still alive when June 12 arrived. The one spike bore three shrunken grains, while the other two bore none. The moisture conditions in both the surface foot and the subsoil were like those in XIII—with negative free moisture (—4.3 per cent) in the former and practically none (0.2 per cent) in the latter. The subsoil was uniformly dry at the different depths. There was a fair development of roots to the very bottom of the subsoil. In this cylinder also the plants perished independently of one another.

CYLINDER WITH 12 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XX differed from XIX in that it was filled with moist soil containing 11.5 per cent free water. All four plants in this did well until the end of April when the four plants had 11 tillers in all. One plant began to die, but the other three continued to grow. They all wilted on May 17 but recovered and put forth 4 spikes which were not yet ripe on June 11. The high temperature of the following day killed all the plants. The earliest spike bore 6 shrunken grains. The surface foot contained —3.8 per cent free water and the subsoil an average of 1.5 per cent, it being quite uniformly distributed. Roots occurred thruout the subsoil, but in the lower foot sections they were much less numerous than in XIX.

TWO CYLINDERS WITH MOISTER SOIL NEAR THE SURFACE.—Cylinders V and VI were filled with air-dry subsoil and surface soil and then to the surface was added the amount of water required to make the total weight of water in the cylinders equal to 18 per cent of the weight of the dry subsoil plus 25 per cent of that of the dry surface soil. The total amount of moisture in V and VI was almost the same as that in XX—8,076 and 8,007 grams against 8,060 grams—but the distribution of this thruout the soil mass was quite different.

The plants in V and VI made the most vigorous growth of all. On March 26 the plants in both cylinders suffered some slight injury from mice. On April 27 the 4 plants in the former had 19 tillers and those in the latter had 20. On that date there were removed from VI three plants having 11 tillers, thus leaving one with 9. The weight of dry matter in the three plants was 4.3 grams. On May 17 the plants in both wilted, the one in VI suffering as much as the four in V. At no time after the thinning of April 27 did the plant in VI appear thriftier than the plants in V. None put forth a spike and all were nearly dead before June 12. The cylinders were opened on June 14. In VI the moisture conditions in both surface soil and subsoil were practically indentical with those in XIX, while the subsoil was very slightly drier in V. Roots were very extensively and uniformly distributed thruout the soil mass. Figure 13 shows well the extent of the development of the roots in both. The weight of roots in the subsoil of both V and VI was three times as great as that of the roots in the subsoil of XIX. The plants in V and VI, having started with about the same amount of soil moisture and having formed a better developed root system, had made a much less economical use of the soil water, practically exhausting it before putting forth spikes, than had those in XIX.

KUBANKA WHEAT.

A series of 6 cylinders, corresponding to those used for the Red Fife wheat, was planted on the same day with Kubanka wheat, ten seeds being used for each. On February 28, when the plants were from 4 to 9 inches high, they were thinned to the most vigorous four in each cylinder. No further thinning was intentionally practiced, but on March 26, mice ate off, almost level with the surface, one plant in VII and one in VIII. Both later put forth tillers. As with the Red Fife wheat, little difference in growth was to be observed during the first month.

Tables 13 and 14 give the data and figures 14 and 15 show the condition of the plants and the distribution of roots in the subsoil.

TABLE 13.—*Data on experiment with Kubanka wheat in 1910.*

	VII	VIII	XI	XV	XVII	XXII
Weight of dry soil and subsoil in cylinder, in grams	43,163	42,55[illegible]	41,121	43,435	44,855	46,665
Weight of water in soil and subsoil in cylinder, February 5, in grams	8,162	8,054	3,220	4,866	6,40[illegible]	[illegible],433
Weight of water in soil and subsoil at opening of cylinder, in grams	2,490	5,376	2,413	2,[illegible]19	3,300	4,845
Weight of water lost	5,672	2,678	807	2,047	3,102	3,588
Time from planting of seed to maturing of plant, days	129	129	93	129	129	129
Height of plant, in inches	21.0	16.0	9.5	11.0	18.0	16.5
Number of spikes	0	3	0	1	3	[illegible]
Number of grains	0	0	0	0	0	18
Weight of grains, air-dry, in grams	0	0	0	0	0	0.70
Weight of leaves, stems, etc., air-dry, in grams	11.1	3.9	0.6	2.6	5.9	5.6
Weight of crop dried at 110° C., in grams	10.0	3.5	0.6	2.3	5.4	5.8
Weight of water lost per gram of crop at 110° C., in grams	567	765	1,345	890	574	618
Weight of roots, dried at 110° C., in second foot, in grams	.034	.037	Traces	.013	.046	.048
Weight of roots, dried at 110° C., in third foot, in grams	.034	.006	.000	.019	.048	.0[illegible]8
Weight of roots, dried at 110° C., in fourth foot, in grams	.036	.000	.000	.017	.012	.007
Weight of roots, dried at 110° C., in fifth foot, in grams	.054	.0[illegible]0	.000	.009	.004	.007
Weight of roots, dried at 110° C., in sixth foot, in grams	.053	.000	.000	.005	Traces	.005
Total weight of roots in subsoil	.211	.043	Traces	.063	.110	.076
Average height of plants on February 28, in inches	6.5	6.0	7.0	8.0	8.5	7.5
Average height of plants on March 5, in inches	9.0	9.0	9.0	10.0	9.0	8.5
Average height of plants on March 12, in inches	10.5	11.0	9.5	10.0	10.5	10.0
Average height of plants on March 18, in inches	12.5	13.0	9.[illegible]	10.5	1[illegible].0	11.0
Average height of plants on March 28, in inches	12.5	14.0	9.0*	10.5	13.0	11.5
Average height of plants on April 2, in inches	12.5	14.0	9.0	10.5	13.0	12.0
Average height of plants on April 9, in inches	13.5	14.0	8.5	10.5	13.0	12.0
Average height of plants on April 16, in inches	14.5	14.0	......	10.0*	14.0	12.5
Average height of plants on April 23, in inches	17.0	14.0	......	10.0	1[illegible].5	13.0
Average heiget of plants on April 30, in inches	20.0	14.0	......	10.0	17.0	14.0
Average height of plants on May 7, in inches	21.0	14.0	......	9.5	1[illegible].[illegible]	1[illegible].0
Average height of plants on May 27, in inches	21.0	16.0	......	11.0	1[illegible].0	16.5
Date of death of last plant	June 14	June 14	May 9	June 14	June 14	June 14
Date of opening cylinder	June 14	June 14	May 13	June 14	June 14	June 14
Per cent of total water in surface foot of soil, February 5	25.0	[illegible]5.0	[illegible]0.0	20.0	20.0	0.1
Per cent of total water in subsoil, February 5	18.0	18.0	5.8	9.8	13.4	17.8
Per cent of total water in surface foot on opening cylinder	6.2	6.3	6.2	5.8	6.4	6.0
Per cent of total water in subsoil on opening cylinder	5.7	13.6	5.8	6.6	7.[illegible]	11.0

*The height reported is that of the highest green point on the plant.

TABLE 14.—*Moisture conditions on opening cylinders with Kubanka wheat in experiment of 1910.*

Depth of section		Free water						Hygroscopic coefficient
		VII	VIII	XI	XV	XVII	XXII	
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
1..........	1-3	—5.2	—5.4	—6.0	—5.8	—5.9	—6.0	9.3
	4	—4.9	—4.9	—5.4	—5.5	—5.0	—5.7	9.3
	5-6	—4.0	—4.3	—4.6	—4.8	—3.6	—4.9	9.3
	7-9	—3.3	—3.6	—3.0	—4.1	—3.0	—3.8	11.0
	10-12	—2.2	—1.9	—1.6	—2.4	—2.0	—1.7	11.0
2..........	13-15	— .3	.8	— .1	.2	.1	.5	5.6
	16-18	.0	2.1	.3	.2	.0	.4	5.6
	19-21	.1	4.5	.2	.5	.1	1.1	5.6
	22-24	.1	5.9	.3	.4	.5	1.6	5.6
3..........	25-27	.1	6.3	.2	.5	.4	2.2	5.6
	28-30	.2	6.7	.2	.8	.5	3.2	5.6
	31-33	.1	7.3	.4	.8	.6	3.8	5.6
	34-36	.2	7.6	.2	.6	.6	4.9	5.6
4..........	37-39	.3	8.4	.2	.5	.6	5.8	5.6
	40-42	.2	8.7	.2	.4	1.0	6.1	5.6
	43-45	.2	8.7	.1	.6	1.0	6.6	5.6
	46-48	.1	9.3	.1	.5	1.8	7.1	5.6
5..........	49-51	.3	9.5	.2	.7	2.8	7.7	5.6
	52-54	.2	9.7	.3	1.2	3.1	7.8	5.6
	55-57	.0	10.0	.2	1.6	3.8	8.1	5.6
	58-60	.1	10.5	.3	1.9	4.4	8.6	5.6
6..........	61-63	.1	11.4	.2	2.4	4.7	8.8	5.6
	64-66	.1	11.9	.4	3.0	4.8	9.0	5.6
	67-69	.1	12.3	.7	3.0	4.4	9.0	5.6
Average....	1-12	—3.9	—3.8	—3.8	—4.3	—3.7	—4.1	10.1
Average....	13-69	.1	8.0	.2	1.0	1.9	5.4	5.6

CYLINDER WITH NO FREE WATER IN THE SUBSOIL.—Cylinder XI was filled, like XIII, with subsoil containing 5.8 per cent total water. The four plants in this fell behind those in the other cylinders at the end of the first month, making no growth after March 12. On March 28 they all wilted and from this time on slowly died, all being dead on May 9, none having put forth a spike or formed a tiller. Four days later the cylinder was opened. The moisture conditions and the root development were almost identical with those in cylinder XIII of the Red Fife wheat series. The free water in the subsoil amounted to only 0.2 per cent, the same as when the seed was planted, and that in the surface foot was —3.9 per cent. Only one very small root, less than two inches long, was found in the uppermost three-inch section of the subsoil; this is not shown in figure 15, having been lost. The same remarks are applicable to the growth of the plants in this cylinder as to those in cylinder XIII. The amount of water lost per gram of dry matter produced was correspondingly high, viz, 1345 grams.

CYLINDER WITH 4 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XV, like XIV in the previous series, was filled with moist subsoil containing 9.8 per cent total water or 4.2 per cent free water. The plants continued to grow until about March 18. On April 2 all were slightly wilted. Later in the month three of the plants began to slowly improve and on April 30 these three carried 5 tillers, but the fourth plant was dying. On May 27 two of these three were dying, but the other had put forth a spike, and altho no distinct growth was made after this date, the plant still gave promise of forming grain as late as the evening of June 11; one other plant, altho dying, was not yet dead, but the remaining two were quite dead. On June 12 both plants died. Two days later, on opening the cylinder, the moisture conditions and root development were found very similar to those in XIV. The free water in the subsoil was a little higher, 1.4 per cent against 1.0 per cent, but was similarly distributed, rising steadily from 0.3 per cent in the second foot to 2.8 per cent in the sixth—practically the wilting coefficient.

Here, as in XIV, the plants did not die simultaneously, altho they all wilted for the first time on the same day. With more favorable weather conditions, it seems probable that grain would have developed in the one spike which had been put forth.

CYLINDER WITH 8 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XVII, corresponding to XIX in the Red Fife wheat series, started with 7.8 per cent free water. Three of the four plants grew steadily without wilting up to June 11, when they had put forth three spikes; the other had begun to die before the end of April. The high temperature of June 12 killed all the plants before any grain had formed. The moisture conditions were somewhat like those of XV but more free water remained. It rose from 0.2 per cent in the second to 4.7 per cent in the sixth

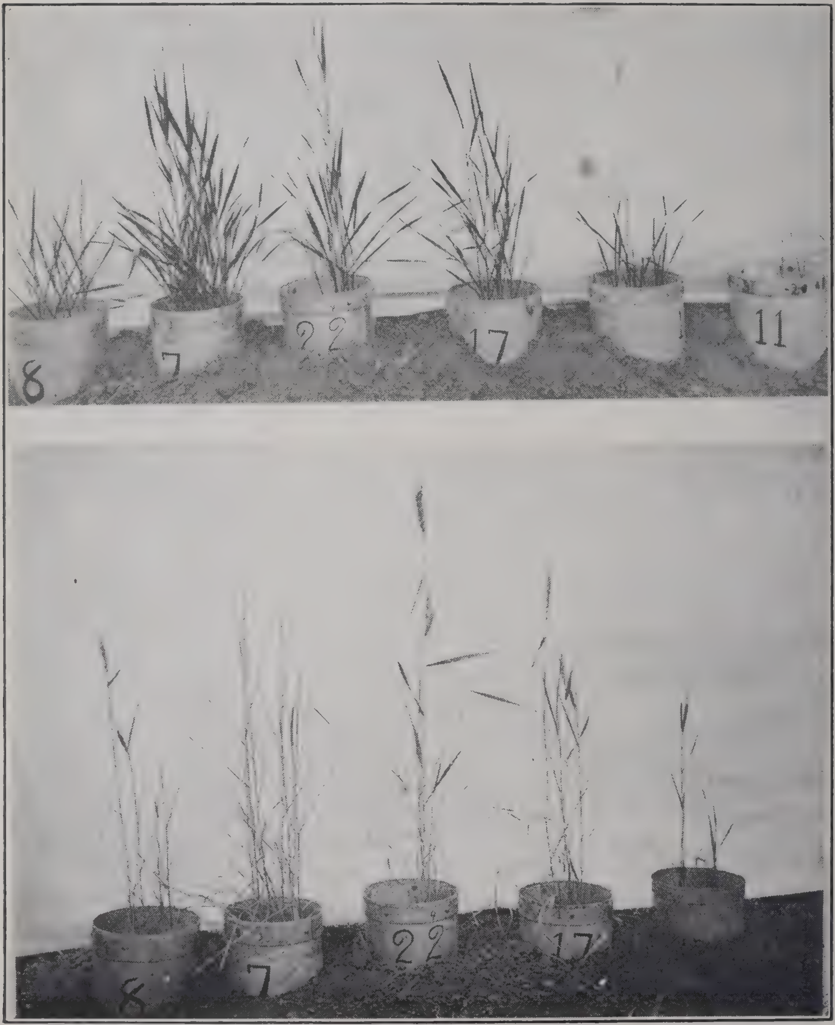

Fig. 14. Kubanka wheat 77 and 123 days after planting; experiment of 1910.

foot. The development of the roots was similar to that in XV, except that there were many more in the second and third feet and very few in the sixth. It seems probable that under favorable weather conditions more or less grain would have been formed. It is interesting to note that in this cylinder, as in XIV and XV, the moisture in the second, third, and fourth feet had been reduced much below the wilting coefficient.

Cylinder with 12 per cent free water in the subsoil.—Cylinder XXII differed from XVII in that the subsoil carried 17.8 per cent total water. Two plants in this ceased to grow about the middle of March and gradually declined, altho neither was actually dead even as late as June 8. Each of the other two plants developed 3 tillers and each produced a spike, the one containing 18 grains but the other forming none. The death of both plants was due to the high temperature of June 12. The subsoil still contained much free water, which increased from 1.1 per cent in the second foot to 8.9 per cent in the sixth. The roots extended to the bottom of the cylinder, but those in the lower por-

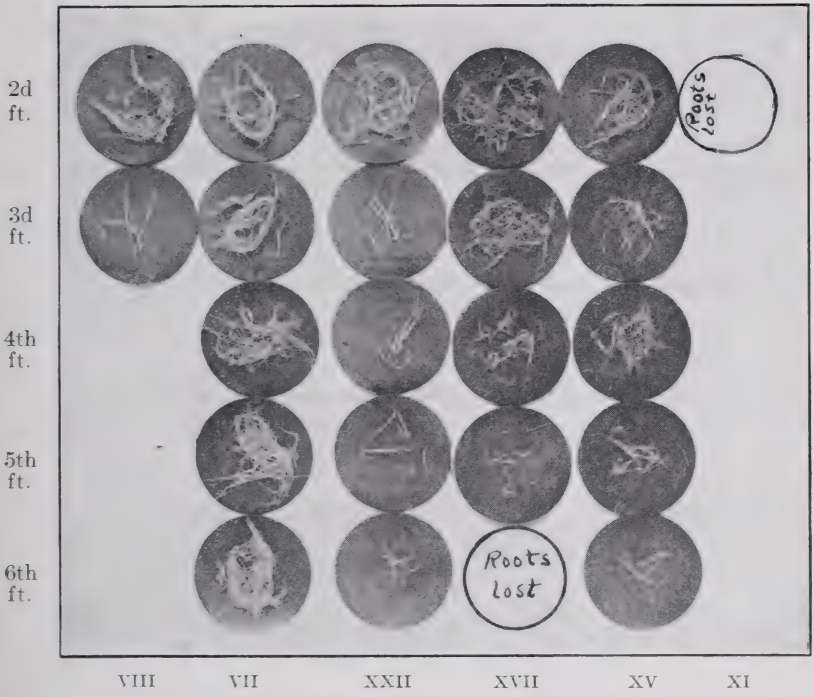

Fig. 15. Roots of Kubanka wheat; experiment of 1910.

tions of the subsoil were not as numerous as those in the second foot. These two plants would doubtless under more favorable temperature conditions have continued a normal development. It seems probable that neither of the two plants which dropped out of competition early had developed roots below the second foot.

TWO CYLINDERS WITH MOISTER SOIL NEAR THE SURFACE.—Cylinders VII and VIII were filled like V and VI described above (page 61).

The four plants in VII made the most vigorous growth of all the Kubanka wheat until early in May. On May 7 they bore 10 tillers in all and five sheaths were swelling. Ten days later the awns on one were showing but after this no growth was made, the plants slowly dying until killed by the high temperature of June 12. Roots had formed in abundance in all parts of the subsoil and the free water had been exhausted.

The plants in VIII on March 18 had 5 tillers while in none of the other five cylinders had more than a single tiller appeared. The plants made little progress from that date until the early part of May when they seemed to take on new life. On June 8 one spike was out and two other spikes were partly out, but all the plants appeared to be dying. On June 12 they died without having formed any grain. Very few roots had developed below the second foot and none below the third. There was an abundance of free moisture in the subsoil, even more than in XXII, it steadily rising from 3.3 per cent in the second foot to 11.9 in the sixth, altho the first foot had no free water.

MILO.

The seed used was from a good head taken in October, 1909, from a field near Cuervo, New Mexico, where a very severe drouth had prevailed thruout the growing season.

The series of 6 cylinders was similar in all respects to those employed with the wheats. In each cylinder eight seeds were planted. On February 28, twenty-three days after planting, when the milo plants were from 4 to 7 inches high, the number was reduced to the most vigorous three in each cylinder. The plants in the different cylinders were much alike in growth until March 19, when those in XII wilted somewhat during the hottest part of the day. On that day the number in each cylinder was again reduced, this time to the one most vigorous plant in each cylinder. The two lots of thinnings were dried and their weights included in those of the total dry matter reported in Table 15. As in the case of the wheat series, little difference among the plants in the different cylinders was observed during the first month.

The moisture conditions of the soil at the death of the plants are shown in Table 16 and in figures 7 to 11. Figure 16 shows the condition of the plants on April 23 and on June 8. The roots separated from the different foot sections of the subsoil are shown in figure 17.

CYLINDER WITH NO FREE WATER IN THE SUBSOIL.—Cylinder XII was filled with subsoil containing 5.8 per cent total water. The three plants in this cylinder wilted on March 19 and two were removed. During the following week the single remaining plant grew a little but from March 19 on it wilted every day and growth had ceased entirely by March 26, its condition steadily growing worse until May 13 when it was practically dead. It was then harvested and the cylinder opened. The dwarfed plant is shown on the left of the upper row in figure 16. As in the case of the corresponding wheat cylinders roots had penetrated only a few inches into the first foot of subsoil and in this also a slight distillation of moisture seems to have taken place. The average amount of moisture in the subsoil was the same as when the experiment was begun. In the portion of the subsoil in which the roots had developed, no free water remained. The amount of water lost per gram of dry matter produced was very large, namely, 1315 grams.

CYLINDER WITH 4 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XVI was filled with moist subsoil containing 9.8 per cent total water. The first signs of injury from drouth were observed on March 26. After this the plant made no growth but remained alive until killed by the high temperature of June 12. Even on May 27 the plant was green to a height of 8½ inches above the soil in the cylinder. Roots had penetrated only to the fourth foot. In the fifth and sixth feet none were found and in these the moisture was as high as when the seed was planted. The surface foot was practically as dry as in any other cylinder, but the upper portion of the subsoil was as moist as that of XVIII and the lower portion was much more moist. This moist condition of the lowest foot and a half is to be attributed to the failure of the plant to develop roots to that depth, while the comparatively high percentage of moisture in the upper portion of the subsoil is to be attributed to the very limited development of roots in this portion. Under less trying conditions the plant might have lived for a considerable time altho it had long ceased to make any growth.

CYLINDER WITH 8 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XVIII was filled with subsoil containing 14.1 per cent total water. The plant in this made a slow but normal growth until the end of April when it had put forth a head part way out of the sheath. On May 13 it was in bloom and four days later showed the first signs of injury from drouth. It made no further growth and formed but a single grain. The seed was ripe but the plant was not dead on June 11. On the following day the high temperature killed the plant. The cylinder was opened 9 days later. The roots were abundant and uniformly distributed thruout the subsoil. The free water in the subsoil had been quite uniformly reduced, with an average of 0.7 per cent.

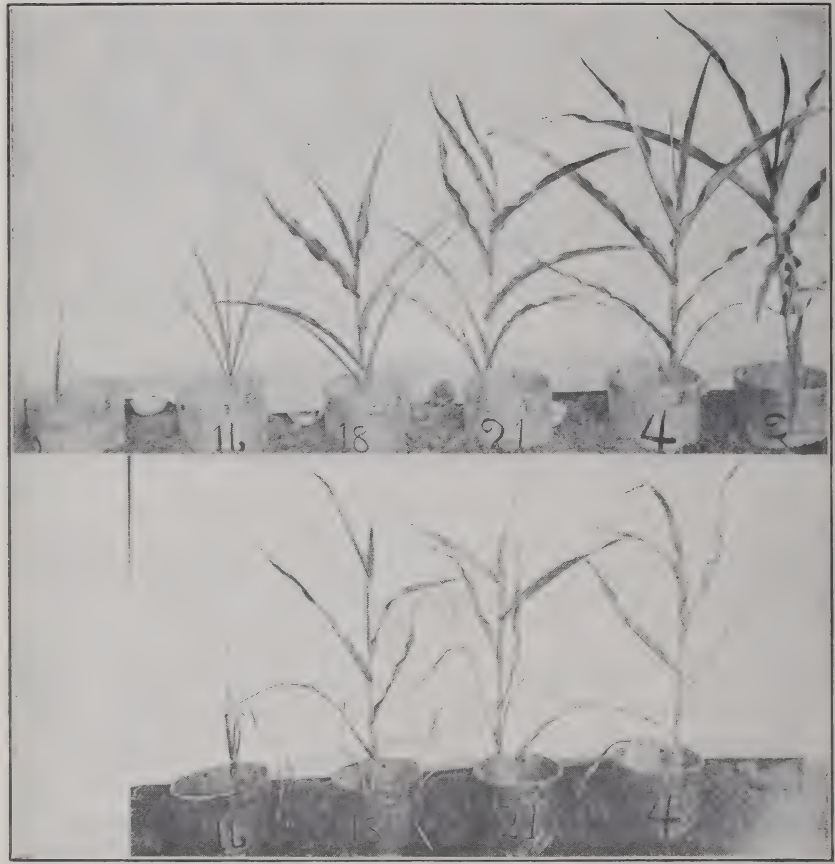

Fig. 16. Milo 77 and 123 days after planting; experiment of 1910.

CYLINDER WITH 12 PER CENT FREE WATER IN THE SUBSOIL.—Cylinder XXI was filled with subsoil containing 18.2 per cent total water. The plant in this made a somewhat more rapid growth than that in XVIII but the two were very similar in growth thruout, forming heads, blooming, and showing signs of injury from drouth at about the same time. Both had ripe seeds and were dying on June 11 but neither was yet quite dead. The plant in XXI bore 21 grains. These two were the only plants in the six cylinders that at any time gave promise of forming heads. In both cylinders the roots were abundant and uniformly distributed thruout the subsoil but in XXI the fine roots were more numerous than in XVIII. In XXI, as in XVIII, the free moisture of the subsoil had been almost exhausted, there being only an average of 0.3 per cent, quite uniformly distributed, at the time of the death of the plant.

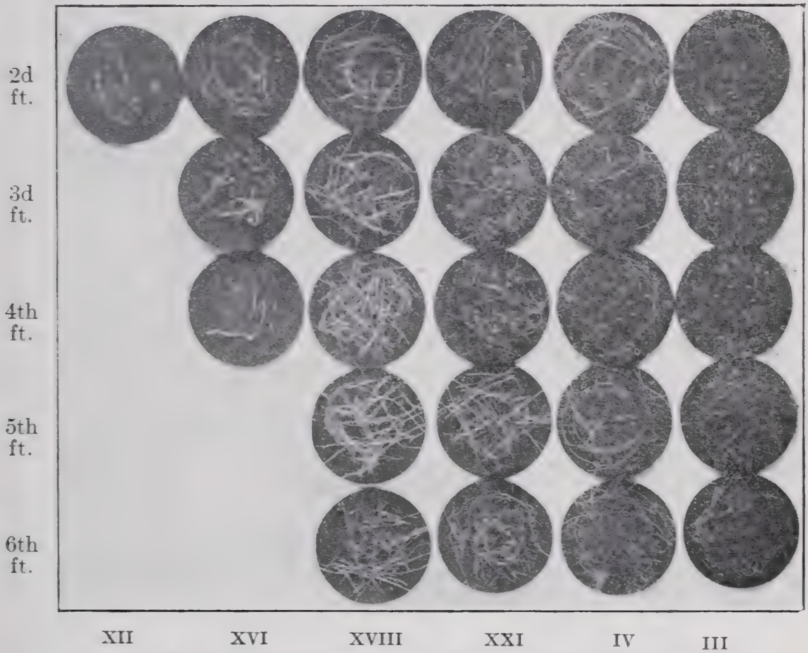

Fig. 17. Roots of milo; experiment of 1910.

TWO CYLINDERS WITH MOISTER SOIL NEAR THE SURFACE.—Cylinders III and IV were filled, as described on page 48, with dry subsoil and surface soil, and then enough water was added to raise the total amount of water to the equivalent of 18 per cent of the subsoil and 25 per cent of the surface foot. During the early part of the experiment the two plants in these two cylinders made

TABLE 15.—*Data on experiment with milo in 1910.*

	III	IV	XII	XVI	XVIII	XXI
Weight of dry soil and subsoil in cylinder, in grams	42,102	40,632	42,296	43,025	44,744	46,430
Weight of water in soil and subsoil in cylinder, February 5, in grams	7,966	7,600	3,303	4,714	6,687	8,555
Weight of water in soil and subsoil at opening of cylinder, in grams	2,490	2,262	2,486	3,369	2,883	2,836
Weight of water lost, in grams	5,476	5,338	817	1,345	3,804	5,719
Time from planting of seed to maturity of plant, days	97	129	97	129	129	129
Height of plant, in inches	34	31	14	15	26	28
Number of heads	0	0	0	0	1	1
Number of grains	0	0	0	0	1	23
Weight of grain, air-dry, in grams	0	0	0	0	0.05	0.70
Weight of leaves, stems, etc., air-dry, in grams	12.6	9.9	0.92	2.0	9.4	12.7
Weight of crop dried at 110° C., in grams	11.5	9.0	0.85	1.8	8.65	12.0
Weight of water lost per gram of crop at 110° C., in grams	476	593	1,315	747	440	477
Weight of roots, dried at 110° C., in 2d foot, in grams	.313	.257	.036	.056	.061	.317
Weight of roots, dried at 110° C., in 3d foot, in grams	.200	.688	.000	.028	.074	.563
Weight of roots, dried at 110° C., in 4th foot, in grams	.510	.808	.000	.012	.158	.224
Weight of roots, dried at 110° C., in 5th foot, in grams	.542	.633	.000	.000	.126	.097
Weight of roots, dried at 110° C., in 6th foot, in grams	.437	.755	000	.000	.124	.155
Total weight of roots in subsoil, in grams	2.002	3.141	.036	.096	.543	1.356
Average height of plants on February 28, in inches	5.0	5.5	6.5	5.0	5.0	4.5
Average height of plants on March 5, in inches	9.0	9.5	9.0	9.5	9.5	9.0
Average height of plants on March 12, in inches	11.5	14.0	12.0	11.0	12.0	12.0
Average height of plants on March 18, in inches	14.0	17.0	12.5	12.5	13.0	14.5
Average height of plants on March 26, in inches	16.5	20.0	14.0	15.0	16.0	18.0
Average height of plants on April 2, in inches	22.0	24.0	14.0	15.0	18.5	20.5
Average height of plants on April 9, in inches	25.0	27.5	13.5*	15.0	20.0	22.0
Average height of plants on April 16, in inches	29.0	31.0	13.5	15.0	22.0	24.5
Average height of plants on April 23, in inches	34.0	31.0	13.5	15.0	24.5	27.0
Average height of plants on April 30, in inches	34.0	28.5*	13.5	15.0	26.0	27.5
Average height of plants on May 7, in inches	32.5*	28.5	?	?	26.0	28.0
Date of death of last plant	May 13	June 14	May 13	June 14	June 14	June 14
Date of opening cylinder	May 13	June 14	May 13	June 14	June 21	June 21
Per cent of total water in surface foot of soil, February 5	25.0	25.0	20.0	20.0	20.0	20.0
Per cent of total water in subsoil, February 5	18.0	18.0	5.8	9.8	14.1	18.2
Per cent of total water in surface foot on opening cylinder	8.0	6.0	6.2	6.5	7.3	7.6
Per cent of total water in subsoil on opening cylinder	5.6	5.5	5.8	8.0	6.3	5.9

* The height reported is to the highest green point on the plant.

TABLE 16.—*Moisture conditions on opening cylinders with milo in the experiment of 1910.*

Depth of section		Free water						Hygroscopic coefficient
		III	IV	XII	XVI	XVIII	XXI	
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
1.	1-3	—5.4	—5.8	—6.2	—5.5	—5.0	—6.0	9.3
	4	—3.3	—5.4	—5.2	—4.7	—4.6	—4.3	9.3
	5-6	—2.0	—4.5	—4.5	—3.5	—3.5	—1.6	9.3
	7-9	— .5	—3.6	—2.9	—2.8	—1.8	—1.3	11.0
	10-12	— .3	—2.3	—1.4	.....	— .5	— .3	11.0
2.	13-15	.1	— .3	— .1	.0	.7	.3	5.6
	16-18	.1	— .2	.0	.6	.8	.4	5.6
	19-21	.3	— .1	.3	.6	.7	.3	5.6
	22-24	.3	— .1	— .1	.6	.7	.3	5.6
3.	25-27	.3	.0	.1	.8	.6	.3	5.6
	28-30	.2	.1	.0	.7	.8	.2	5.6
	31-33	.2	.1	— .1	.9	.9	.3	5.6
	34-36	.0	.1	— .3	1.3	1.0	.3	5.6
4.	37-39	.0	.1	— .1	1.8	.5	.6	5.6
	40-42	.0	— .1	.1	2.4	.8	.5	5.6
	43-45	.0	— .2	.2	2.8	.7	.2	5.6
	46-48	— .1	.0	.2	3.4	.9	.3	5.6
5.	49-51	.0	— .1	.3	3.9	.6	.3	5.6
	52-54	— .1	— .1	.5	3.8	.7	.3	5.6
	55-57	— .2	— .2	.5	4.3	.7	.5	5.6
	58-60	— .3	.1	.5	4.4	.7	.5	5.6
6.	61-63	.1	.1	.5	4.5	.8	.3	5.6
	64-66	.0	.1	.7	4.4	.7	.2	5.6
	67-69	.0	.0	.6	4.7	.6	.2	5.6
Average	1-12	--2.1	—4.1	—3.8	--3.6	—2.8	—2.5	10.1
Average	13-69	.0	.0	.2	2.4	.7	.3	5.6

the most vigorous growth of all (see the upper row in figure 16) but they had completely exhausted the free water before any plants had put forth heads. These two were the only milo plants which formed any tillers. Each formed one, that in the case of IV being removed on March 26 and that in the case of III on April 16, both being less than 6 inches long. At the end of April both plants were already suffering seriously from drouth and neither showed any sign of putting forth a head. Both were in worse condition on May 13. There was little difference between the two plants at this time but that in III seemed to be in the better condition; the plant in this was harvested and the cylinder opened. That in IV was left a month longer. It was almost entirely dead on June 11 and was harvested three days later, being then quite dry.

The roots in both were abundant and uniformly distributed. The surface soil of IV contained 2.0 per cent less water than that of III but there was little difference in the amount of moisture in the subsoil—it being practically exhausted in both. If, as is probable, the subsoil moisture was at least as low in IV as in III on May 13, it is of interest that it was no lower at the end of another month, one of very high temperature.

The loss of moisture from the surface foot of soil of IV which occurred during the last month, assuming that it was as dry as in III on May 13, is to be attributed almost entirely to direct evaporation, as the free moisture had already been entirely removed.

MEXICAN BEANS.

Mexican pink beans, from the Sulphur Spring Valley Dry-Farm of the Arizona Experiment Station, were planted on February 5 in cylinders I and II, filled as described on page 48, the surface foot of soil containing 25 per cent and the subsoil 18 per cent total water. On February 22 the plants were thinned to the most vigorous two in each cylinder. On March 29 all the plants were in bloom, the two in I being 7 and 9 and those in II being 9 and 13 inches high. Many pods formed on each of the plants but most of these failed to fill. By April 23 leaves were beginning to drop from all four; the photograph (figure 18) was taken on that day. On April 27 the two plants in I wilted badly and did not recover, both being dead on April 30. A week later all the leaves seemed quite dry, but the pods and stems not being dry the cylinder was left until May 13. The plants in II held out for over a week longer, wilting for the first time on May 7. They were dead two days later and quite dry by May 13.

On the death of the plants, as will be seen from Table 18 and figure 7, there was a very uniform distribution of moisture thruout the five feet of subsoil, there being practically no difference even between that in the second foot and that in the lower part of the sixth foot. In the surface foot the moisture content increased rapidly from the top to the bottom. The average content of free moisture in the first foot was —1.5 per cent and in the five feet of subsoil 0.8 per cent. The roots were numerous thruout the subsoil and quite uniformly distributed, as will be seen from both Table 17 and figure 19.

TABLE 17.—*Data on experiment with beans in 1910.*

	I	II
Weight of dry soil and subsoil in cylinder, in grams	43,593	44,102
Weight of water in subsoil, February 5, in grams	8,220	8,333
Weight of water in subsoil, May 13, in grams	2,849	2,967
Weight of water lost in 97 days, in grams	5,371	5,366
Average height of plants, in inches	8	11
Number of pods which produced seeds	3	4
Number of seeds	14	14
Weight of seeds, air-dry, in grams	2.24	2.77
Weight of leaves, stems, and pods, air-dry, in grams	5.25	5.10
Weight of crop, dried at 110° C., in grams	6.92	7.10
Weight of water lost per gram of crop, in grams	776	756
Time from planting of seed to death of plants, in days	97	97
Weight of roots, dried at 110° C., in 2d foot, in grams	.063	.082
Weight of roots, dried at 110° C., in 3d foot, in grams	.073	.081
Weight of roots, dried at 110° C., in 4th foot, in grams	.084	.118
Weight of roots, dried at 110° C., in 5th foot, in grams	.091	.111
Weight of roots, dried at 110° C., in 6th foot, in grams	.074	.094
Total weight of roots in subsoil, in grams	.385	.486
Date of death of last plant	May 13	May 13
Date of opening cylinder	May 13	May 13
Per cent of total water in surface foot of soil, February 5	25.0	25.0
Per cent of total water in subsoil, February 5	18.0	18.0
Per cent of total water in surface foot on opening cylinder	7.5	7.6
Per cent of total water in subsoil on opening cylinder	6.4	6.6

TABLE 18.—*Moisture conditions on opening cylinders with beans, experiment of 1910.*

Depth of section		Total water		Free water	
		I	II	I	II
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1.	1-3	3.1	3.5	—6.2	—5.8
	4	4.5	4.5	—4.8	—4.8
	5-6	5.6	5.5	—3.7	—3.8
	7-9	9.8	9.6	—1.2	—1.4
	10-12	12.1	12.3	1.1	1.3
2.	13-15	6.4	6.5	0.8	0.9
	16-18	6.3	6.5	0.7	0.9
	19-21	6.3	6.4	0.7	0.8
	22-24	6.4	6.5	0.8	0.9
3.	25-27	6.3	6.4	0.7	0.8
	28-30	6.1	6.3	0.5	0.7
	31-33	6.3	6.1	0.7	0.5
	34-36	6.2	6.3	0.6	0.7
4.	37-39	6.3	6.4	0.7	0.8
	40-42	6.3	6.3	0.7	0.7
	43-45	6.4	6.4	0.8	0.8
	46-48	6.3	6.3	0.7	0.7
5.	49-51	6.3	6.2	0.7	0.6
	52-54	6.3	6.3	0.7	0.7
	55-57	6.5	6.3	0.9	0.7
	58-60	6.5	6.4	0.9	0.8
6.	61-63	6.5	6.3	0.9	0.7
	64-66	6.7	6.4	1.1	0.8
	67-69	6.7	6.3	1.1	0.7
Average	1-12	7.5	7.6	—2.6	—2.5
Average	13-69	6.4	6.3	0.8	0.7

The total moisture in the subsoil at the death of the two plants was 6.4 and 6.3 per cent respectively, being 1.8 and 1.9 per cent below the wilting coefficient. It seems improbable that this large amount of water was removed between the time that the plants wilted permanently and the time that the cylinders were opened.

SUMMARY OF EXPERIMENT OF 1910.

The subsoil of the two unplanted cylinders at the beginning of the experiment held nearly twice as much water as the same subsoil would have retained under field conditions. The surface foot of soil, however, was not wetter than it might have been found in the field after a period of wet weather. The loss of water during the 97 days of the experiment was equivalent to not more than two inches of rain and was confined chiefly to that in the surface foot.

The plants in all the cylinders evidently died from lack of sufficient soil moisture. The slow dying of many was cut short by a temperature of 124° F., which, altho not fatal in itself, caused such a rapid transpiration that water could not be absorbed rapidly enough to meet the requirements because of the small amount of free water in the portions of the subsoil where there was an extensive development of roots. The plants were already dead or dying in all the cylinders except one of Red Fife wheat and two of Kubanka wheat.

In their ability to exhaust the soil moisture before dying, the four different crop plants showed little difference, but in their ability to continue alive after first showing serious injury from drouth they showed marked differences. The interval between wilting and death in the case of beans amounted to only a few days but in that of milo and wheat it extended to many weeks.

Where there was a well-developed root system and no remarkably high temperature occurred before the death of the plants, the moisture content of the soil was reduced almost to the hygroscopic coefficient.

Plants in the same cylinder wilted and died independently of one another and simultaneous wilting was not followed by simultaneous death.

Plants started in cylinders with comparatively little free water in the subsoil lived longer than some started in cylinders with a very moist subsoil.

The plant roots did not penetrate the subsoil where this contained practically no free water and penetrated very slowly where the water content was only a little above the wilting coefficient. While there appeared to be a close connection between the early development of the plants in the different cylinders and the quantity of roots in the subsoil, there was little connection between the quantity of roots and the final development of the plants. Where roots were uniformly distributed, there was a uniform loss of free water from the different levels, but where the development of roots was markedly lacking in uniformity there were distinct differences in the loss of free water.

In one cylinder the removal of the aerial portions of the most of the plants, after the root system had been fully developed and the soil moisture so reduced that further root development could not take place, proved of little or no benefit to the remaining plants.

Calculated to an acre basis the yield of grain was below 6 bushels per acre except in the case of beans, where it exceeded

1,000 pounds. In the production of total dry matter the milo made the most economical use of the water, but in that of seed the beans made much the most economical use; but if the cylinder had carried several times as much soil, thus giving each plant much more water, the latter might not have been the case. The yield of total dry matter in the case of these cylinders with an initial water content similar to what might be expected to the same depth and in the same type of subsoil in summer fallowed fields varied from 500 to 4,000 pounds per acre. The portion of the free water in the surface foot of soil at the time of planting the seed had much less effect on the production of dry matter than had an equal amount in the subsoil.

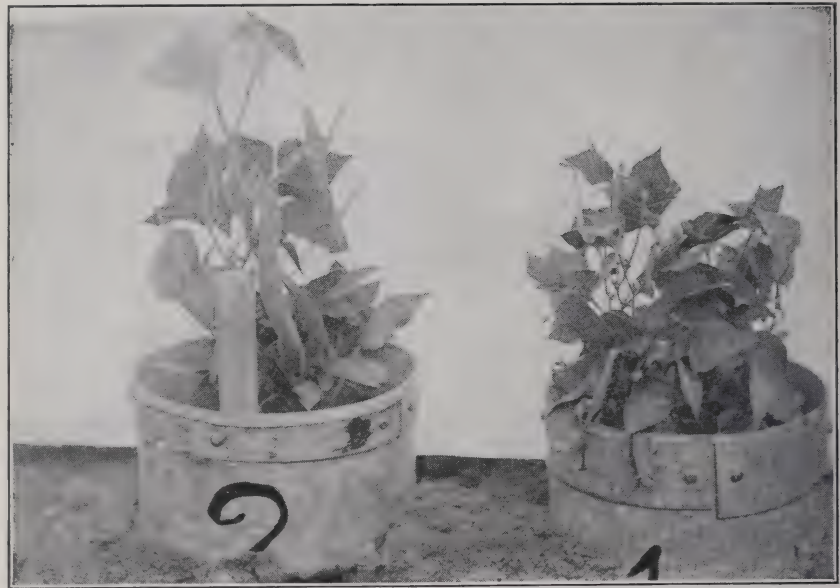

Fig. 18. Mexican beans 77 days after planting; experiment of 1910.

A very hard crust formed below the mulch in all the planted cylinders.

EXPERIMENT WITH LOESS SOILS FROM DIFFERENT PARTS OF THE TRANSITION REGION. EXPERIMENT OF 1911.

Loess[1] forms the chief surface deposit of more than half of Nebraska, occurring over the whole eastern end and extending westward for more than 300 miles. The different parts of this formation have been exposed to comparatively uniform temperature conditions but to great differences in precipitation, if we assume that since the close of the glacial epoch there has been but little change in the climate of what is now Nebraska. In the extreme eastern part the normal precipitation is over 30 inches, while in the southwestern corner it is less than 20, there being a gradual decrease from east to west as shown on the accompanying map. While the precipitation decreases from east to west, there is a rapid rise in the rate of evaporation. As the precipitation falls chiefly during the growing season there is but little seepage from the level prairies in the eastern portion and practically none from those in the western. Uniformity in physical properties has long been recognized as characteristic of the Nebraska loess and a recent chemical study[1] has shown that, except in the content of calcium carbonate, which increases from east to west, the chemical composition is very uniform.

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[1] Barbour, E. H. Nebraska Geological Survey, vol. 1, 1903, p. 169.

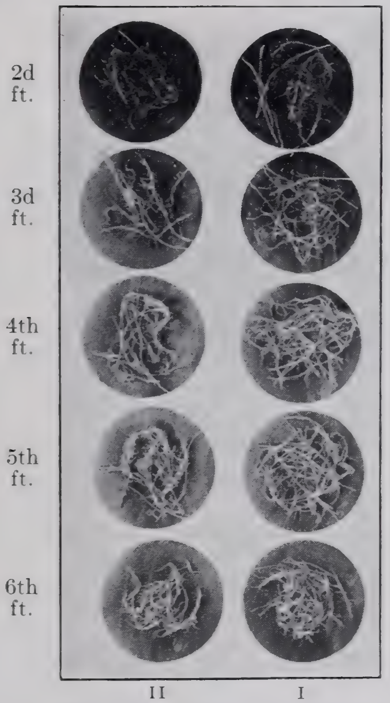

Fig. 19. Roots of Mexican beans; experiment of 1910.

Field studies of soil moisture had indicated that there was a considerable difference in the rooting habits of some crop plants between the eastern and the western portions of the loess in Nebraska, and to determine whether there was a gradual change from west to east this experiment was carried out in 1911. The location of the places where the soils were secured are indicated on the map in figure 20. At each of the five places an excavation was made and about 150 pounds of soil taken from each of the first 6 feet. These bulk samples were shipped to the Experiment Station where each soil, in dry condition, was reduced to a fine state of division and mixed by passing it several times thru a one-eighth-inch screen as previously described (page 47). This screening at the same time served to remove nearly all the roots. Three cylinders were filled with the soils from each of these places.

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[1] Alway, F. J. Composition of the Loess Soils of the Transition Region. Eighth International Congress of Applied Chemistry, 1912, Report of Section VII, p. 11.

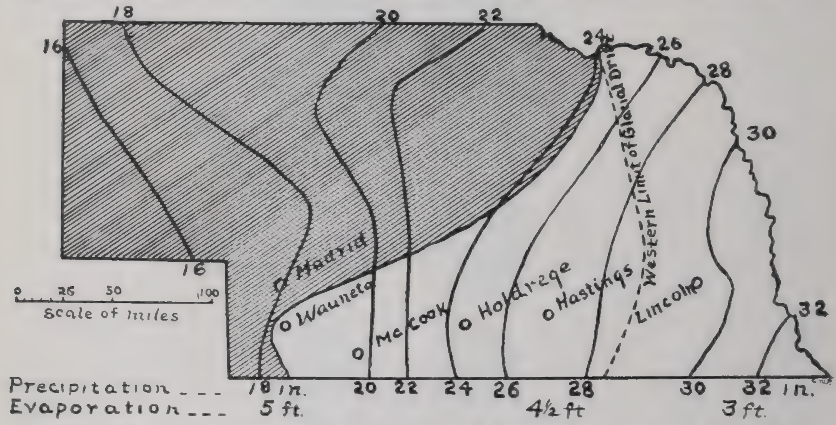
18
20
22
16
24
26
28
30
32
16
Western Limit of Glacial Drift
Madrid
Wauneta
McCook
Holdrege
Hastings
Lincoln
0 25 50 100
Scale of miles
Precipitation ___ 18 in. 20 22 24 26 28 30 32 in.
Evaporation ___ 5 ft. 4½ ft 3 ft.

Fig. 20. Map showing the loess region of Nebraska (unshaded) and the sources of the samples used, as well as the normal annual precipitation and evaporation.

Besides the 15 cylinders mentioned, 8 others were used in the experiment. Six were filled with the same H O soils used in 1910, but instead of keeping the upper and the lower half of the surface foot separate the previously unused portions of these were mixed and used as one lot of soil. The hygroscopic coefficient was found to be practically the same as the average of the two parts used in 1910. These 6 are referred to as the H O cylinders. The surface 6 inches of soil from a field from the Experiment Station Farm was used to fill two cylinders which are referred to as those of Surface Soil.

The hygroscopic coefficients of the soils used are given in Table 19. The numbers given for the H O soils and for the surface soil are the averages of a large number of determinations, and those for the others are the averages of three determinations made on different days.

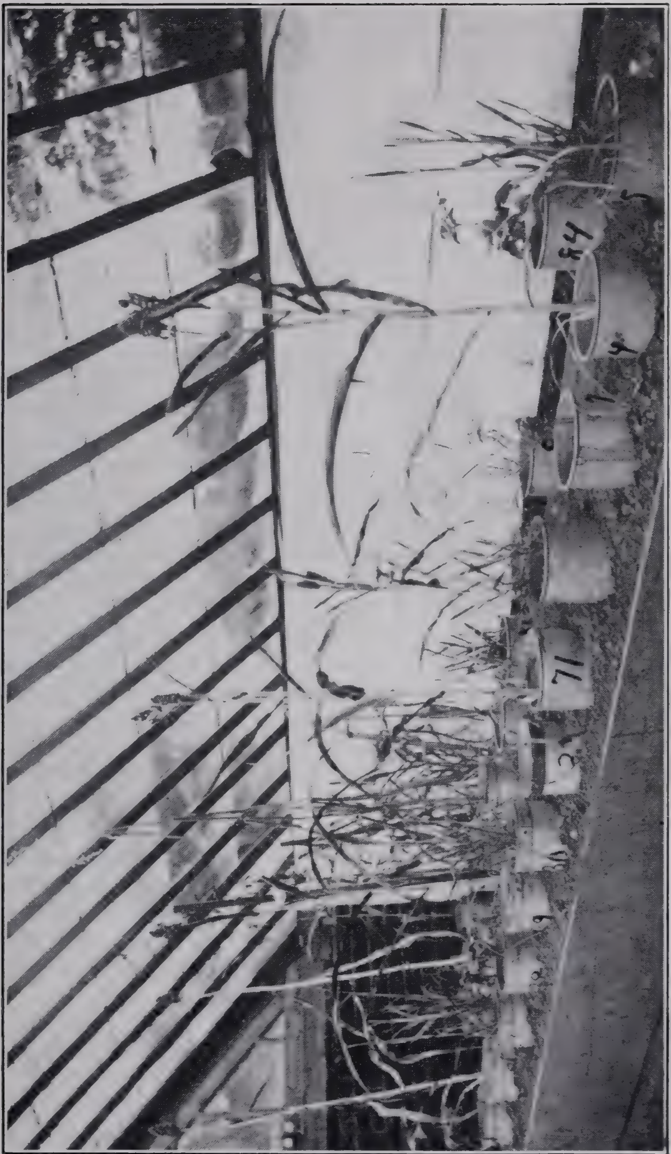

Fig. 21. Experiment of 1911; 96 days after planting the seed.

TABLE 19.—*Hygroscopic coefficients of soils used in the experiment of 1911.*

Depth, foot	H O	Wauneta	McCook	Holdrege	Hastings	Lincoln	Surface soil
1	10.0	9.2	9.4	10.1	10.7	12.1	11.3
2	5.6	9.5	11.0	11.7	13.2	15.3	11.3
3	5.6	9.9	9.6	12.0	11.7	14.6	11.3
4	5.6	10.1	9.0	10.6	11.5	13.2	11.3
5	5.6	9.5	8.8	9.7	10.8	13.2	11.3
6	5.6	8.6	8.4	9.6	10.5	13.5	11.3
Average .	6.3	9.5	9.4	10.6	11.4	13.6	11.3

The 23 metal cylinders, 6 feet long and similar in all respects to those employed in the preceding two years, were filled with dry soil as in the earlier experiments, then saturated with water and drained as described above (page 32). The loess soils. especially those from the more easterly portions of Nebraska, contain so much clay and fine silt and, accordingly, are so easily puddled when worked in a wet condition that it was not considered advisable to attempt to add the water to the different foot sections of soil before introducing these into the cylinders. Seven cylinders were planted to Red Fife wheat, 7 to Milo, 6 to Mexican pink beans, and 2 to maize. Into one cylinder young mesquites were transplanted. After planting the seeds, a one-inch layer of dry soil was added to the surface and the cylinders sunken in a pit in the greenhouse as in the preceding year. The general arrangement of the cylinders is shown in figure 21.

The records of the daily maximum and mean temperatures as well as of the humidity and the evaporation from a free water surface are given in Tables 2 to 5. No whitewash was used on the windows of the greenhouse. Altho much better ventilation was provided the temperature was very high, the daily maximum being below 100° F. on only 7 days between May 15 and July 24, the date when the last plant died. On July 5 the maximum temperature out of doors was 110° F., while inside the greenhouse it was 130° F. These high temperatures hastened the death of many of the plants.

The same precautions were observed as in the preceding two years regarding the formation of crevices between soil column and cylinder wall.

As soon as the plants died they were removed from the cylinders and the weight of dry matter determined. In most cases the cylinders were at once opened and the soil moisture determined. The roots were separated from the surface foot as well as from the subsoil, photographed, dried, and weighed.

A summary of the moisture conditions in the different cylinders and of the crops is given in Table 20, and figure 21 shows the cylinders near the close of the experiment. The moisture conditions on the death of the plants are shown in figures 22 to 28.

TABLE 20.—*Cylinders used in the experiment of 1911.*

Cylinder No.	Designation	Crop	Total water at time of planting, 1 to 6 feet	Date of death of last plant	Date of opening of cylinder
			Per cent		
78	H O........	Red Fife wheat.	27.1	June 17	June 22
79	H O........	Milo	25.2	May 30	May 30
77	H O........	Mexican beans.	25.8	May 5	May 6
24	H O.......	Maize.........	24.3	May 30	May 30
76	H O	Maize.........	25.1	May 30	May 30
25	Wauneta ...	Red Fife wheat.	30.9	July 7	July 7
26	Wauneta ...	Milo	30.2	July 5	July 7
27	Wauneta . .	Mexican beans.	29.2	June 8	June 22
30	McCook....	Red Fife wheat.	31.4	July 12	July 12
29	McCook....	Milo	31.1	July 24	July 28
28	McCook....	Mexican beans.	30.7	July 18	July 18
72	Holdrege ...	Red Fife wheat.	34.4	June 26	June 26
71	Holdrege ...	Milo	32.3	July 24	July 28
31	Holdrege ...	Mexican beans.	32.5	May 18	May 31
75	Hastings ...	Red Fife wheat.	35.1	July 18	July 18
74	Hastings ...	Milo	34.5	July 5	July 7
73	Hastings ...	Mexican beans.	34.6	June 6	June 22
82	Lincoln.....	Red Fife wheat.	35.9	June 27	June 27
83	Lincoln.....	Milo	36.9	April 29	May 6
84	Lincoln. ..	Mexican beans.	36.4	June 27	June 27
80	Surface.....	Red Fife wheat.	38.1	July 12	July 12
81	Surface.....	Milo	37.7	June 20	June 21

RED FIFE WHEAT.

On February 20, eight sprouted seeds were planted in each of 7 cylinders. Four days later all the plants had appeared above the surface and during the next two weeks they were thinned to 4 to a cylinder. Up to April 11 there were no very marked differences between the plants in the 7 cylinders. All were alive and appeared healthy on April 15 except in the Hastings cylinder, where one plant was dead, and in the Lincoln cylinder, where one plant was dying. On this date the plants in the Lincoln cylinder and in the cylinder of surface soil were considerably less thrifty than those in the 5 others. On April 30 there was one dead plant in each of the McCook, Holdrege, and Hastings cylinders and two in the Lincoln cylinder. Spikes were forming in all except that of surface soil. In vigor the plants seemed to decline in the following order: H O, Wauneta, McCook, Holdrege, Hastings, Surface Soil, and Lincoln. Those in the H O cylinder closely resembled those in the Wauneta and those in the cylinders of Holdrege and Hastings soil were very similar. The plants in Lincoln soil were in very bad condition, appearing to be seriously suffering from drouth. During the next month none of the plants made any progress and all were injured during the first week of June with its continued high temperature. The general conditions on May 27 may be seen from figure 21. None of the plants had died since those recorded on April 30 but many were dying by June 9.

The plants in the H O cylinder were all dead on June 17; only one spike had formed and that bore no grain. On June 26 the plants in the Holdrege cylinder were dead, having formed only one spike and this being barren. On the next day the plants in the Lincoln cylinder were all dead. The extremely unfavorable weather during the last week of June and the early part of July caused the remaining plants to die rapidly, all being dead by July 18. A single spike—on a plant in the Wauneta cylinder—formed grain. Additional data on these wheat plants are given in Table 21.

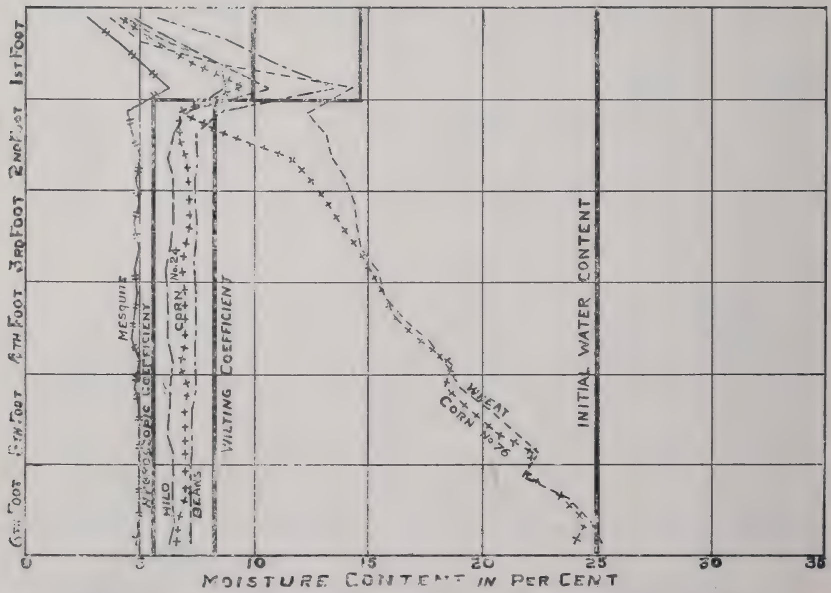

Fig. 22. Final moisture conditions in cylinders of H O soil.

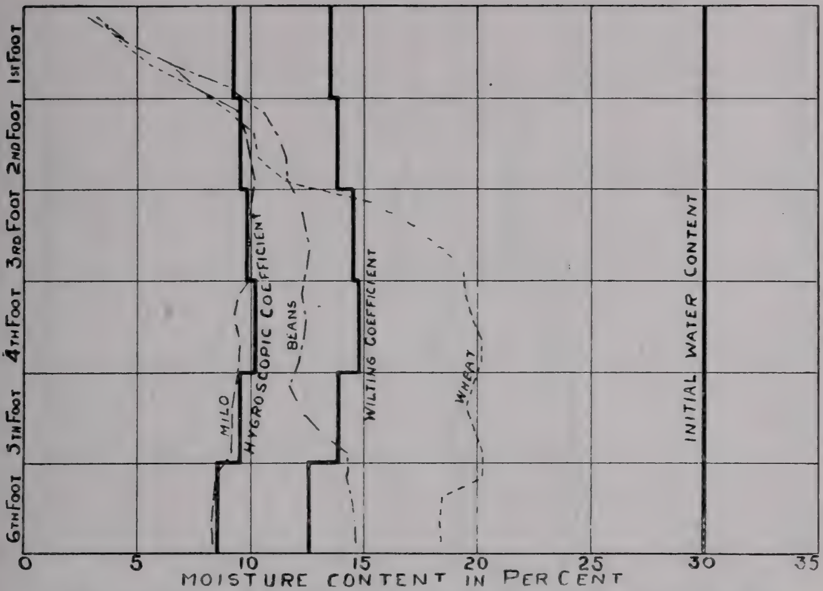

Fig. 23. Final moisture conditions in cylinders of Wauneta soil.

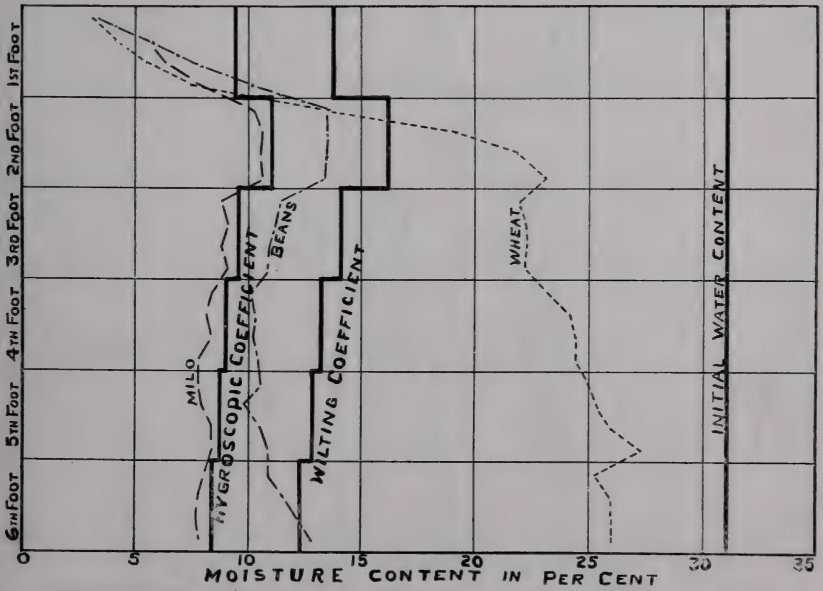

Fig. 24. Final moisture conditions in cylinders of McCook soil.

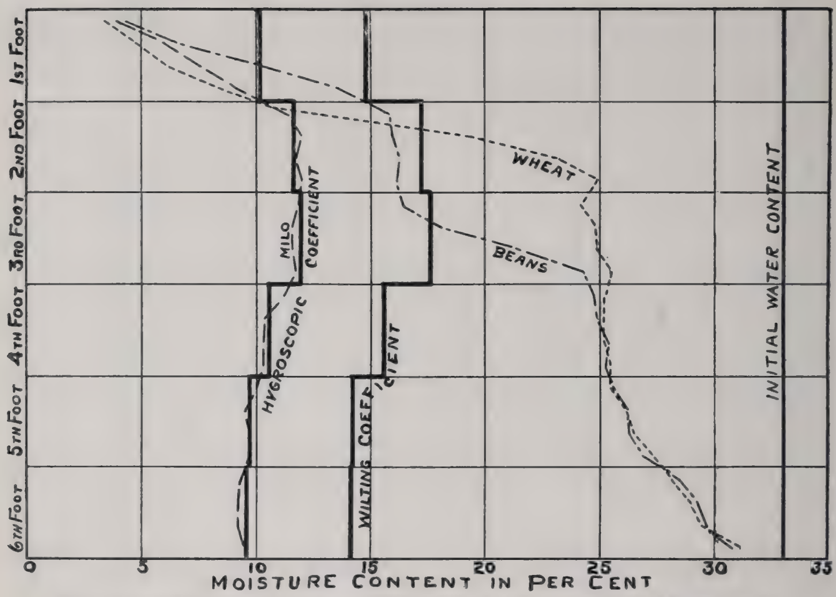

Fig. 25. Final moisture conditions in cylinders of Holdrege soil.

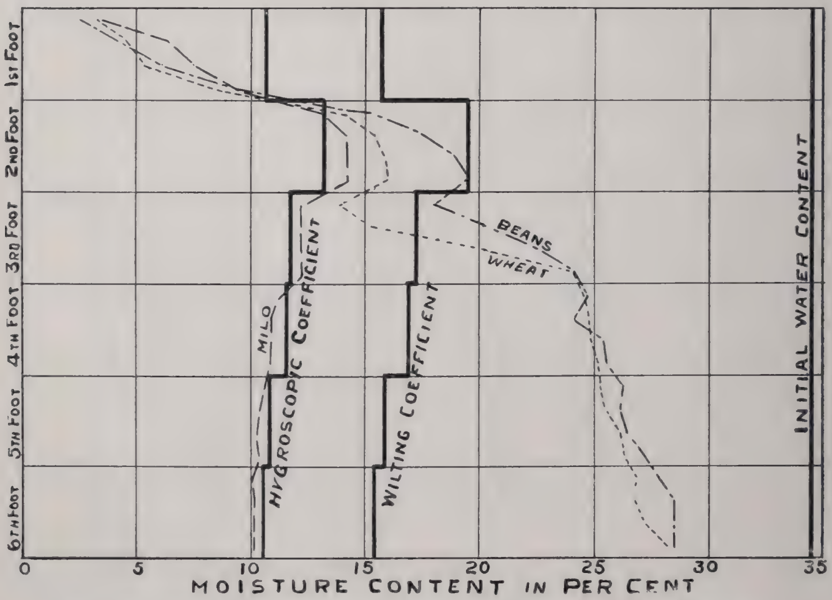

Fig. 26. Final moisture conditions in cylinders of Hastings soil.

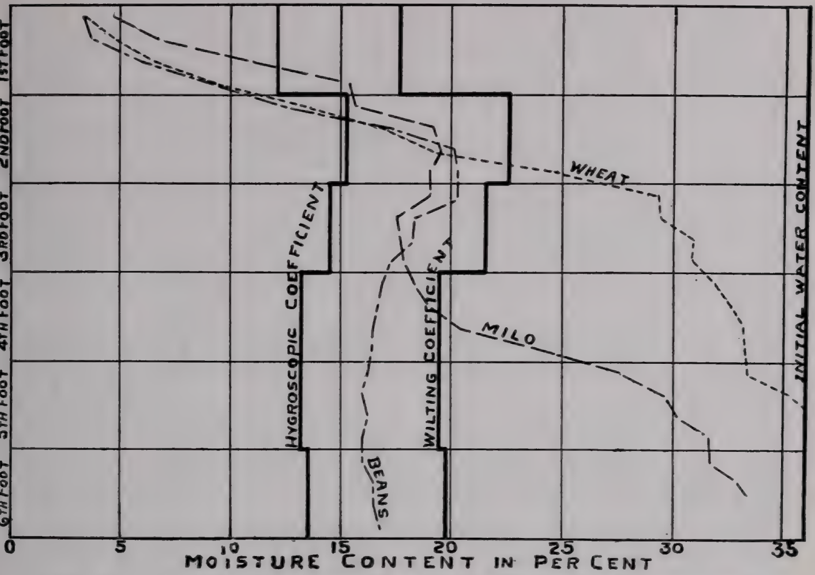

Fig. 27. Final moisture conditions in cylinders of Lincoln soil.

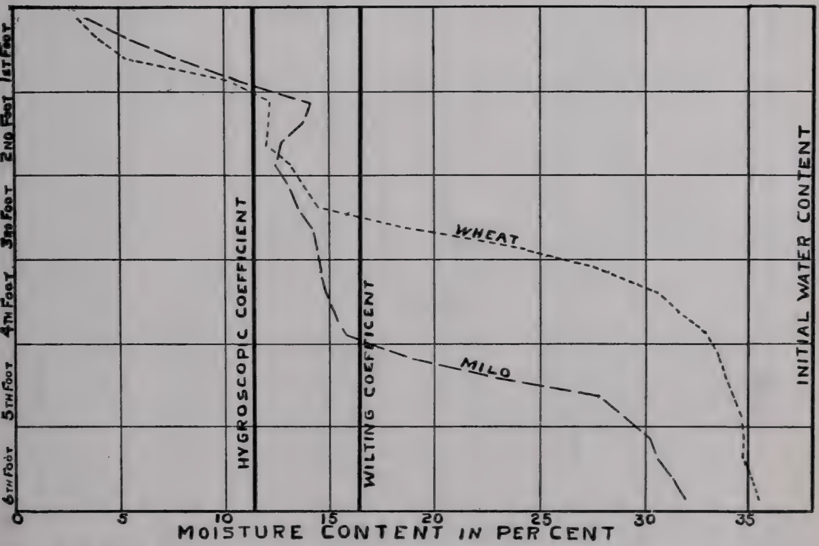

Fig. 28. Final moisture conditions in cylinders of surface soil.

TABLE 21.—*Data on experiment with Red Fife wheat in 1911.*

	H O Soil	Wauneta	McCook	Holdrege	Hastings	Lincoln	Surface Soil
Weight of dry soil in cylinder, in grams	44,679	44,622	43,148	42,156	41,248	34,841	34,643
Weight of water in soil on February 20, in grams	11,850	13,494	13,239	14,146	14,118	11,963	12,445
Weight of water in soil on opening cylinder, in grams	7,238	6,827	8,802	9,274	8,043	9,651	7,829
Weight of water lost, in grams	4,612	6,667	4,437	4,872	6,075	2,312	4,616
Time from planting seed to death of last plant, in days	107	127	132	116	138	117	132
Av. height on June 17 of plants with heads, in inches	10.5	15.0	11.0	14.0	14.0	14.0	10.0
Number of spikes	1	5	4	1	3	1	2
Number of grains	0	14	0	0	0	0	0
Weight of grain, air dry, in grams	0	0.324	0	0	0	0	0
Weight of crop, dried at 110° C., in grams	2.0	6.9	4.2	3.8	6.1	1.8	2.2
Weight of water, lost per gram of crop, in grams	2,306	966	1,056	1,282	996	1,284	2,098
Weight of roots, at 110° C., in 1st foot, in grams	0.056	0.154	0.237	0.209	0.231	0.054	0.015
Weight of roots, at 110° C., in 2d foot, in grams	0.003	0.099	0.016	0.119	0.010	0.008	0.043
Weight of roots, at 110° C., in 3d foot, in grams	0.003	0.008	0.014	0.006	0.006	0.000	0.006
Weight of roots, at 110° C., in 4th foot, in grams	0.003	0.013	0.014	0.004	0.023	0.000	Traces
Weight of roots, at 110° C., in 5th foot, in grams	Traces	0.008	0.002	0.002	0.022	0.000	0.000
Weight of roots, at 110° C., in 6th foot, in grams	0.001	0.006	0.003	0.001	0.006	0.000	0.000
Total weight of roots in the 6 feet, in grams	0.066	0.288	0.286	0.341	0.298	0.062	0.064
Total weight of roots below surface foot, in grams	0.010	0.134	0.049	0.132	0.067	0.008	0.049
Date of death of plant	June 17	July 7	July 12	June 26	July 18	June 27	July 12
Date of opening cylinder	June 22	July 7	July 12	June 26	July 18	June 27	July 12
Per cent of total water in soil of cylinder, February 20	27.1	30.9	31.4	34.4	35.1	35.9	38.1
Per cent of total water in surface foot on opening cylinder	8.0	5.2	5.0	5.9	5.5	6.0	5.7
Per cent of free water in surface foot on opening cylinder	—2.0	—4.0	—4.4	—4.2	—5.2	—6.1	—5.6
Per cent of total water in 2-6 ft. on opening cylinder	17.9	17.3	23.5	25.2	22.3	32.1	26.0
Per cent of free water in 2-6 ft. on opening cylinder	12.3	7.8	14.1	14.5	10.8	18.1	14.7

TABLE 22.—*Free water on opening cylinders with Red Fife wheat in 1911.*

Depth of section		H O Soil	Wauneta	McCook	Holdrege	Hastings	Lincoln	Surface Soil
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	1-4	—6.2	—6.0	—6.3	—6.7	—7.4	—8.6	—8.2
	5-6	—5.0	—4.9	—5.3	—5.4	—6.1	—7.4	—7.2
	7-9	—1.2	—3.5	—4.0	—3.9	—5.4	—5.5	—5.7
	10-12	4.3	—1.7	—1.9	—1.0	—1.9	—2.8	—0.9
2	13-15	6.7	—0.4	2.6	1.2	1.0	—1.6	0.9
	16-18	7.5	0.6	8.1	7.7	2.2	1.8	0.8
	19-21	7.8	0.8	10.9	11.5	2.7	3.7	0.7
	22-24	8.4	1.9	13.1	13.2	2.8	9.5	1.9
3	25-27	8.8	5.4	12.4	12.2	2.3	14.7	2.5
	28-30	8.9	7.3	12.6	12.8	3.5	14.8	3.3
	31-33	9.1	8.7	12.7	12.9	8.5	16.3	7.3
	34-36	9.8	9.5	12.6	13.5	12.4	16.2	12.8
4	37-39	10.1	9.4	14.2	14.6	13.1	18.6	17.0
	40-42	11.1	9.7	15.2	14.6	13.3	19.4	19.3
	43-45	12.1	10.1	15.5	14.6	13.4	19.9	20.4
	46-48	12.8	10.1	15.5	14.9	13.6	19.9	21.6
5	49-51	13.4	10.4	16.2	15.8	14.5	20.1	22.2
	52-54	14.7	10.1	16.6	16.5	14.8	22.1	22.5
	55-57	15.5	10.4	17.2	16.8	15.3	23.2	23.0
	58-60	16.7	10.7	18.5	17.6	15.5	25.1	23.4
6	61-63	16.2	11.6	16.9	18.6	16.4	25.6	23.5
	64-66	18.2	9.7	16.5	19.4	16.3	29.4	23.5
	67-69	19.2	9.6	18.2	19.9	16.7	31.2	23.8
	70-71	19.5	9.7	18.2	21.5	17.6	32.4	24.2
Average	1-12	—2.0	—4.0	—4.4	—4.2	—5.2	—6.1	—5.6
Average	13-71	12.3	7.8	14.2	14.5	10.8	18.1	14.7

The crevice between soil column and cylinder wall extended to 6, 15, 6, 6, 24, 18, and 23 inches, respectively, in passing from the western to the eastern soils, but it was found well filled in the first four and filled to a depth of 12 inches in the other three.

Roots penetrated to the sixth foot in all the cylinders except the Lincoln and the Surface Soil, but were very few in number below the surface foot, as may be seen from Table 21 and figure 29. The Wauneta and the Hastings cylinders showed the most extensive root development.

The moisture conditions on the death of the plants are shown in Table 22. An abundance of free moisture was present at some depth in each cylinder, the moist soil extending upwards from the bottom. In every cylinder, however, the free moisture was practically exhausted from that portion of the soil in which roots had been freely developed. This is evident from a comparison of figure 29 with Table 22. This very close connection between the root distribution and the exhaustion of free water existed in the case of the foot sections and still more closely in that of the three-inch sections; altho the roots were not separated and weighed from the three-inch sections their abundance in these sections was recorded at the time of opening the cylinders.

While the plants all died from want of water, they did so with plenty of water just beyond the soil depths in which the roots were freely developed. The slight development of roots in the moist soil was evidently not sufficient to supply the plants with water rapidly enough to maintain life under the extremely unfavorable temperature conditions to which they were exposed.

MILO.

On February 20, six milo seeds were planted one inch deep in the moist soil in each of the 7 cylinders. Three days later the plants appeared above the surface. At the end of two weeks the number in each cylinder was reduced to the one most vigorous plant.

All did about equally well during the first seven weeks after planting, altho the plants on the H O and Wauneta soils were somewhat the tallest at the end of that time. The plant in the Lincoln cylinder died during the second week in April. On all the surviving plants heads were appearing by the middle of April and by the end of the month all were in bloom and appeared fairly vigorous. No tillers formed on any of the plants but branches formed on some. On May 6 a branch from 2 to 6 inches long had appeared from the second axil of each of the plants in the Holdrege and Hastings cylinders and from both the second and the third axils of the plant in Surface Soil but there

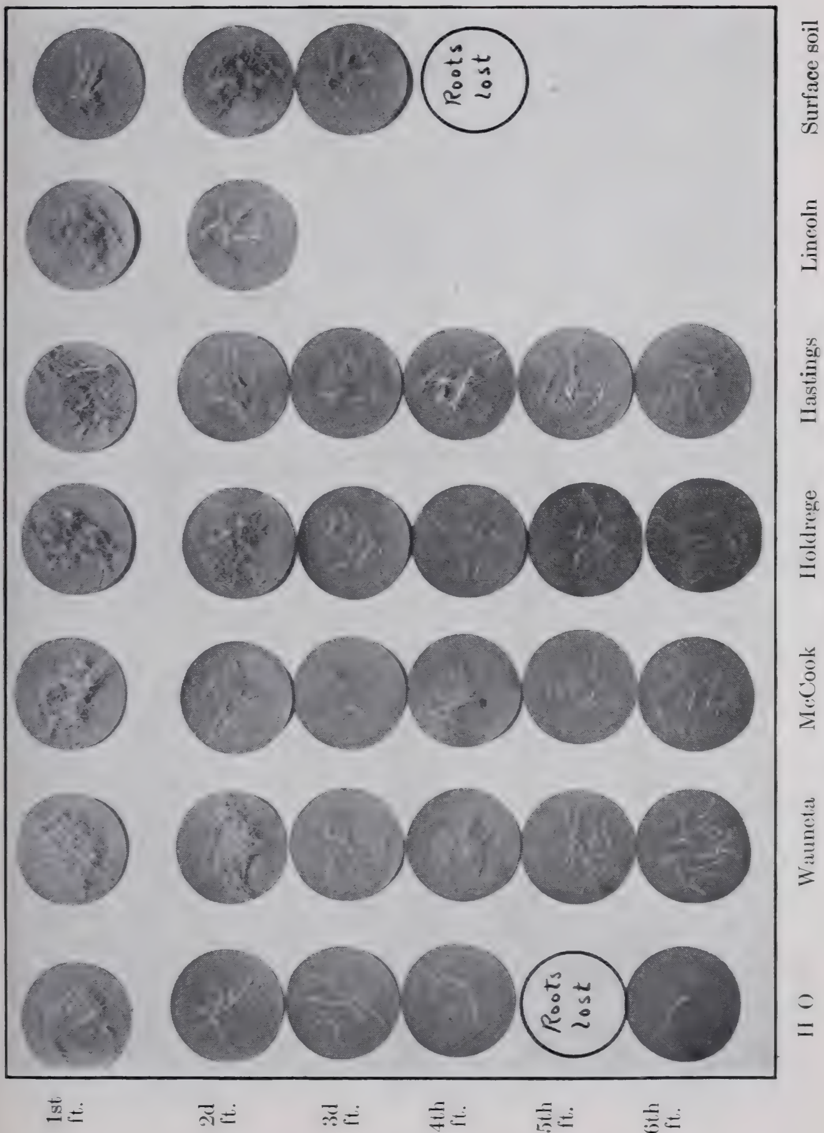

Fig. 29. Roots of Red Fife wheat; experiment of 1911.

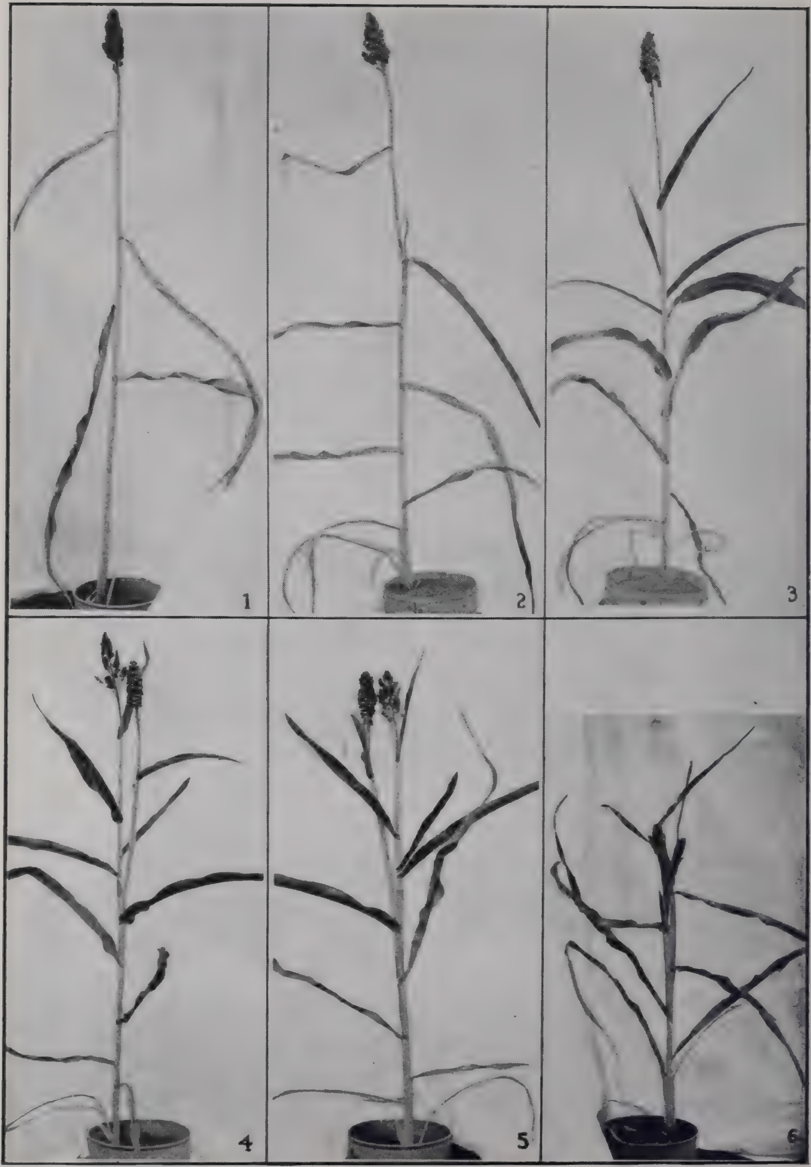

Fig. 30. Milo 96 days after planting; 1, H O; 2, Wauneta, 3, McCook; 4, Holdrege; 5, Hastings; 6, Surface soil.

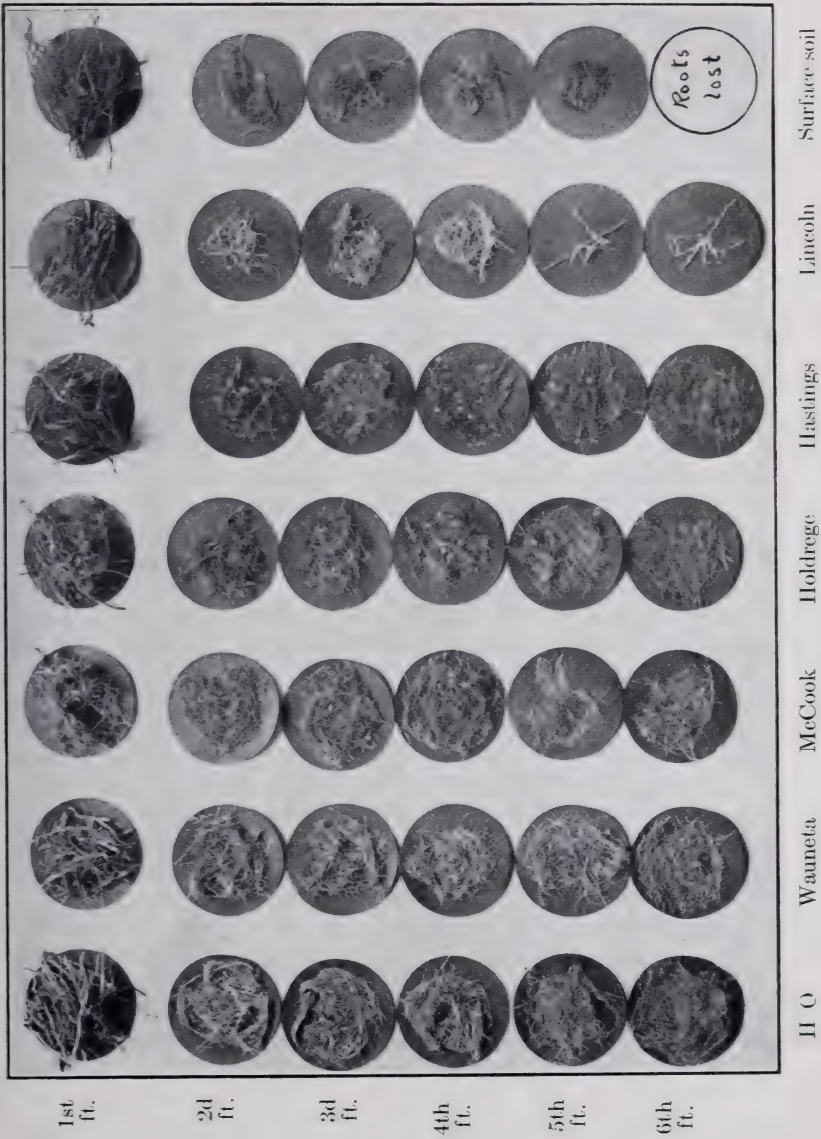

Fig. 31. Roots of milo, experiment of 1911.

was no sign of branching in the case of the plants in the H O, Wauneta, and McCook cylinders. From that time on there was much less uniformity in the development of the plants in the different cylinders.

Figure 30 shows the condition of 6 of the plants on May 27, when they had all reached their full development; that on Lincoln soil had died and had been removed a month before. Table 23 gives the data on the experiment and Table 24 shows the moisture conditions. The distribution of roots is shown in figure 31.

On the H O soil the plant matured one head and died without putting forth any branch. By May 18 the leaves were all dead but the seed was slightly soft. Twelve days later the grain was hard and the entire plant dead and quite dry. The plant (fig. 30) had formed a good head bearing 308 seeds. The cylinder was opened that day. The roots were abundant and uniformly distributed (fig. 31 and Table 24) thruout the subsoil. The free water in the surface foot had fallen to —2.9 while that in the subsoil had been uniformly reduced to 0.7 per cent, 1.9 per cent below the wilting coefficient.

The plant in the Wauneta cylinder put forth a branch soon after May 6 but by May 18 this had ceased to grow, being then 3.5 inches long. On May 30 the seed was practically ripe and the leaves of the main stalk were dead but the branch was still quite green. The latter continued alive until July, thruout June gradually dying back from the tip. Even after the first adverse days of July it showed some signs of life, but was quite dead on July 5. The size of the branch is shown in figure 30, taken on May 27. The development of this branch, which had a long lease of life after the main stalk died, is the only point in which the development of the plant in the Wauneta cylinder differed markedly from that in the H O cylinder. Like the latter it formed a good head and this bore 319 seeds. The cylinder was opened two days after the death of the plant. The distribution of roots resembled that in the H O cylinder. The free water in the surface foot had been reduced to —3.8 per cent and in the subsoil to approximately zero.

The plant in the McCook cylinder differed but little in development from that in the Wauneta cylinder. It formed a branch at the same time as the latter and this on May 13 was 8.0 inches long, and on May 30, when it had three leaves, it was 9.5 inches long (fig. 30), after which it ceased to make any appreciable growth. On May 30 the seed was ripe but all the rest of the plant, except the lowest leaves, was green. On June 17 all the leaves except those on the branch were dead, but the branch was still alive and none of its leaves showed signs of injury from drouth. Even the adverse conditions of the first week in July failed to kill the branch, but from that time on it gradually died. On July 24 it was quite dead and the plant was harvested, it bearing 190 seeds. The cylinder was opened four days later. The root distribution was similar to that in the two cylinders just described. The surface foot contained —3.6 per cent free water and the subsoil an average of —0.6 per cent, the latter being quite uniformly distributed when it is considered that the subsoil consisted of five different soils.

The plants in the Holdrege and Hastings cylinders were very similar in their development. On May 6 both had formed branches, 3 and 2 inches long respectively. On May 30 the plants were still quite green and on each the first head was ripe and a second, formed on the branch, was in bloom (fig. 30, 4 and 5). The second head on each was ripe by the end of June and the plant in the Hastings cylinder was dead by July 5, while the other was not entirely dead until July 24. In the case of each the first head bore a fair amount of seed, 142 and 177 grains respectively, while the heads on the branches bore only 2 and 3 kernels. Roots in both cylinders were abundant thruout the subsoil. The surface foot contained less than —3.0 per cent free water and the subsoil in both contained practically none.

On April 15 the plant in the Lincoln cylinder, not yet having put forth a head, was seen to be dying, altho on the day before it had shown no injury. Two days later it was dead and quite dry, the whole plant remaining as green as tho it had been cut off and dried in the sun. It was evident that the sudden death of this plant was due to some other cause than lack of moisture in the soil and this view was confirmed by the moisture data obtained when the cylinder was opened on May 6. There was an abundance of free water in the fifth and sixth feet and from 3 to 5 per cent even in the second and third feet. The moisture content of the second and third feet was, however, from 2 to 3 per cent below the wilting coefficient while that of the upper three-fourths of the fourth foot was at the wilting coefficient. Roots extended to the bottom of the cylinder, but were not numerous below the fourth foot.

TABLE 23.—*Data on experiment with milo in 1911.*

	H O Soil	Wauneta	McCook	Holdrege	Hastings	Lincoln	Surface Soil
Weight of dry soil in cylinder, in grams	44,963	44,026	43,630	42,553	41,163	35,749	34,756
Weight of water in soil on February 20, in grams	10,956	13,012	13,267	13,437	13,863	12,304	12,360
Weight of water in soil on opening cylinder, in grams	2,878	3,772	3,621	4,255	4,404	7,543	5,920
Weight of water lost, in grams	8,078	9,240	9,646	9,182	9,459	4,761	6,440
Time from planting seed to maturing or death of plant, in days	99	135	154	154	135	68	120
Height of plant, in inches	39.5	36.5	32.5	28.2	27.5	19.0	19.0
Number of heads	1	1	1	2	2	1	2
Number of seeds	308	319	190	144	180	0	5
Weight of seeds, air-dry, in grams	8.03	11.10	7.10	4.83	5.94	0	0.165
Weight of stalks, leaves, etc., air-dry, in grams	17.0	14.7	14.5	15.6	15.9	11.90	16.5
Weight of crop, dried at 110° C., in grams	22.80	23.49	19.66	18.59	19.99	10.88	15.07
Weight of water lost per gram of crop at 110° C., in grams	354	393	481	484	473	438	427
Average weight of seed, air-dry, in grams	.026	.035	.037	.034	.033	....	.033
Weight of roots, at 110° C., in 1st foot, in grams	2.21	.93	1.87	2.89	3.32	1.42	1.51
Weight of roots, at 110° C., in 2d foot, in grams	.22	.31	.22	.16	.13	.04	.05
Weight of roots, at 110° C., in 3d foot, in grams	.27	.21	.22	.07	.13	07	.03
Weight of roots, at 110° C., in 4th foot, in grams	.21	.13	.25	.08	.18	.09	.03
Weight of roots, at 110° C., in 5th foot, in grams	.19	.21	.10	.20	.23	.01	.04
Weight of roots, at 110° C., in 6th foot, in grams	.32	.29	.08	.31	.12	.01	....
Total weight of roots in the 6 feet, in grams	3.42	2.08	2.74	3.71	4.11	1.64	1.66
Total weight of roots below the first foot, in grams	1.21	.115	0.87	.82	.79	.22	.15
Height of plant on April 15, in inches	33	26	19.5	21.5	21.5	19.0	19.0
Height of plant on April 20, in inches	37	34	30.0	25.0	24.5	....	19.5
Height of plant on April 29, in inches	39.5	37	32.5	28.5	28.0	....	19.5
Date of death of plant	May 30	July 5	July 24	July 24	July 5	April 29	June 20
Date of opening cylinder	May 30	July 7	July 28	July 28	July 7	May 6	June 21
Per cent of total water in soil of cylinder,* February 20	25.2	30.2	31.1	32.3	34.5	36.9	37.7
Per cent of total water in surface foot† on opening cylinder	.1	5.4	5.8	6.7	6.7	9.5	6.8
Per cent of free water in surface foot on opening cylinder	—2.9	—3.8	—3.6	—3.4	—4.0	—2.6	—4.5
Per cent of total water in 2-6 ft. on opening cylinder	6.3	9.4	8.8	10.6	11.5	23.4	19.1
Per cent of free water in 2-6 ft. on opening cylinder	0.7	—0.1	—0.6	—0.1	0.0	9.4	7.8

* This refers to all the soil below the surface mulch of air dry soil.

† This refers to the whole of the surface foot, including the mulch.

TABLE 24.—*Free water on opening cylinders with milo in the experiment of 1911.*

Depth of section		H O Soil	Wauneta	McCook	Holdrege	Hastings	Lincoln	Surface Soil
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1..........	1-4	—5.2	—6.3	—6.0	—6.1	—7.2	—7.3	—7.9
	5-6	—3.5	—4.5	—3.8	—4.1	—4.3	—5.3	—6.0
	7-9	—1.5	—2.7	—3.1	—2.5	—3.2	—1.1	—3.5
	10-12	—1.3	—1.5	—1.5	—1.0	—1.2	3.3	—0.7
2..........	13-15	....	—0.1	—0.7	—0.3	0.1	0.4	2.8
	16-18	0.9	0.3	—0.4	0.3	1.0	3.8	2.6
	19-21	0.6	0.5	—0.5	0.1	1.0	4.2	1.5
	22-24	0.8	0.6	—0.4	0.3	1.1	3.7	1.2
3..........	25-27	0.8	0.1	—0.7	—0.1	0.5	4.4	1.8
	28-30	0.8	0.0	—0.5	—0.3	0.4	3.0	2.3
	31-33	0.7	0.1	—0.7	—0.3	0.4	3.1	2.9
	34-36	0.5	0.1	—0.5	—0.2	0.5	3.2	3.1
4..........	37-39	0.6	—0.5	—0.5	0.6	—0.3	5.1	3.4
	40-42	0.6	—0.8	—0.8	—0.3	—0.6	5.7	3.5
	43-45	0.6	—0.6	—0.6	—0.3	—0.6	7.2	3.9
	46-48	0.8	—0.6	—1.1	—0.3	—0.7	10.7	4.5
5..........	49-51	0.7	—0.1	—0.9	0.3	—0.2	14.4	7.3
	52-54	0.7	—0.3	—0.8	—0.1	—0.4	16.4	11.2
	55-57	0.6	—0.3	—0.4	0.0	—0.5	16.9	16.5
	58-60	0.8	—0.4	—0.4	0.0	—0.4	18.4	....
6..........	61-63	0.8	0.0	—0.3	—0.2	—0.5	18.1	18.9
	64-66	0.8	—0.2	—0.5	—0.4	—0.4	19.4	19.4
	67-69	0.9	—0.3	—0.6	—0.4	—0.4	20.2	20.0
	70-71	0.7	—0.3	—0.5	—0.2	—0.4	....	20.6
Average.....	1-12	—2.9	—3.8	—3.6	—3.4	—4.0	—2.6	—4.5
Average.....	13-71	0.7	—0.1	—0.6	—0.1	0.0	9.4	7.8

The plant in surface soil developed much like the plants in the Holdrege and Hastings cylinders, but unlike these it formed two branches. The second did not grow more than a few inches but the first formed a head. Neither this nor the head on the main stalk emerged fully from the sheath. The head on the branch formed two seeds and that on the main stalk three. On May 30 the plant was dying and on June 20 was quite dead. The cylinder was opened on the next day. Roots reached to the bottom of the cylinder but those in the lower portion were few in number. The separation of the roots in the case of this cylinder was very difficult on account of the large number of old root fragments originally present in the soil. Those from the sixth foot were lost before being photographed. Only in the case of the surface foot was the free water exhausted, but in the next three feet of soil, while the moisture content was considerably above the hygroscopic coefficient, it was below the wilting coefficient. In the lowest two feet free water was still abundant, there being 19.3 per cent in the sixth foot.

The crevice between soil column and cylinder wall had reached to 6, 6, 9, and 9 inches in the case of the H O, Wauneta, McCook, and Lincoln cylinders respectively. In the case of the Holdrege and Hastings cylinders a small crevice extended to 48 and 42 inches respectively. In the case of the surface soil a large crevice, one-fourth inch wide, had formed to 30 inches and a smaller one, one-eighth inch wide, to 48 inches. This had been filled by the spatula with fine, dry soil which on opening the cylinder was found to completely fill the crevice to a depth of 12 inches but not below. For reasons already given (p. 36) it is safe to consider that these crevices had little or no effect upon the exhaustion of the soil moisture.

The five plants from the H O, Wauneta, McCook, Holdrege, and Hastings cylinders are quite comparable with the ten plants[1] from which the seed had been obtained, altho they were somewhat taller, weighed more, and produced more seed than the original plants. The comparison is shown in Table 25.

Judging from root distribution, final moisture conditions, and observed changes in the condition of the plants, the death of the plants in the five cylinders of soil from the areas west of Lincoln was due entirely to exhaustion of the water supply. In four cases, viz. Wauneta, McCook, Holdrege, and Hastings, the conditions were extremely favorable to the complete exhaustion of the water, in that after a very extensive root system had been developed thruout the soil mass the death of the main portion of each plant greatly reduced the transpiring surface, thus permitting transpiration to continue for a long time before the death of the plants.

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[1] Secured by the writer from a field near Cuervo, N. M., in September, 1910. The seed planted was from the mixture of the seed from ten plants.

TABLE 25.—*Comparison of plants grown under field conditions in 1910 with those grown in greenhouse in 1911.*

	Ten original plants from Cuervo, New Mexico, 1910	Five plants grown in cylinders 1911
Average height of plant, in inches	13.0	32.8
Average weight of seed per plant, air-dry, in grams	3.91	7.40
Average number of seeds per plant	144	228
Average weight of single seed, in grams	0.027	0.032
Average weight of total dry matter at 110° C., in grams	9.88	20.89

MEXICAN BEANS.

Using seed from the same source as that employed in the preceding year, on February 20 five germinated beans were planted in each of six cylinders. On March 1 all except the Wauneta and McCook cylinders had one or more plants above the surface. Mice ate off a number of the plants and on March 14 more seeds were planted in those cylinders in which plants had been destroyed while in each of the others the number of plants was reduced to the most vigorous four. Part of those from the second planting died within the first three weeks after appearing above the surface, probably for the reason that the older plants with their more extensive root systems prevented the younger ones obtaining the minimum amount of water required.

On April 15 the plants were very uneven in growth. In the H O cylinder there were four of the early ones; these were all in bloom and were more vigorous than those in any other cylinder. The Wauneta cylinder had only three, all from the first planting. These also were all in bloom and nearly as vigorous as the preceding. The McCook cylinder had three small plants from the second planting. The Holdrege cylinder carried one early plant in bloom and two late plants, but both the latter were dead. In the Hastings soil there was only one early plant in bloom together with two small late plants, while in the Lincoln cylinder there was one early plant in bloom and two small late plants, both the latter being dead. From this time on the differences between the plants in the different cylinders became still more marked. The data from the experiment are summarized in Table 26 and the moisture conditions at the close of the experiment are shown in Table 27. Figure 32 shows the distribution of roots thruout the six feet.

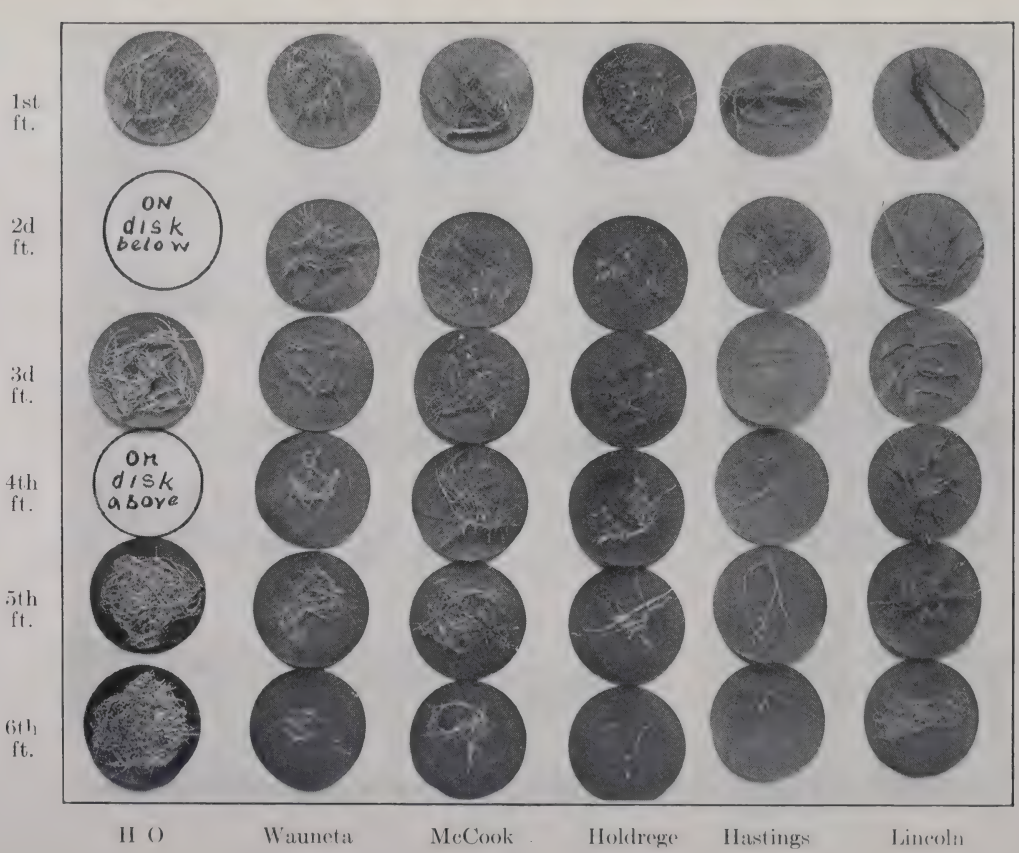

Fig. 32. Roots of Mexican beans, experiment of 1911.

TABLE 26.—*Data on experiment with Mexican beans in 1911.*

	H O Soil	Wauneta	McCook	Holdrege	Hastings	Lincoln
Weight of dry soil in cylinder, in grams	44,849	43,772	43,772	41,900	41,334	35,040
Weight of water in soil on February 20, in grams	11,339	12,502	13,068	13,296	14,077	11,920
Weight of water in soil on opening cylinder, in grams	3,498	5,034	4,684	8,757	8,556	5,326
Weight of water lost, in grams	7,841	7,468	8,384	4,539	5,521	6,594
Time from planting to death of last plant, in days	74	108	126	85	87	127
Number of plants	4	3	3	3	3	1
Number of pods which produced seed	5	6	1	2	2	2
Number of seeds	17	17	2	9	2	5
Weight of seeds, air-dry, in grams	2.98	4.45	0.35	1.88	0.46	1.71
Weight of crop, dried at 110° C., in grams	8.51	9.14	4.32	4.41	3.22	6.06
Weight of water, lost per gram of crop, in grams	921	817	1,941	1,029	1,714	1,088
Weight of roots, at 110° C., in 1st foot, in grams	0.305	0.255	0.316	0.288	0.199	0.203
Weight of roots, at 110° C., in 2d foot, in grams	0.216	0.142	0.198	0.062	0.154	0.110
Weight of roots, at 110° C., in 3d foot, in grams		0.032	0.129	0.059	0.005	0.055
Weight of roots, at 110° C., in 4th foot, in grams		0.028	0.127	0.044	0.009	0.060
Weight of roots, at 110° C., in 5th foot, in grams	0.123	0.059	0.135	0.021	0.032	0.053
Weight of roots, at 110° C., in 6th foot, in grams	0.150	0.009	0.036	0.003	0.003	0.059
Total weight of roots in the 6 feet, in grams	0.794	0.525	0.937	0.477	0.402	0.540
Total weight of roots below surface foot, in grams	0.489	0.270	0.621	0.189	0.203	0.337
Date of death of last plant	May 5	June 8	July 18	May 18	June 6	June 27
Date of opening cylinder	May 6	June 22	July 18	May 31	June 22	June 27
Per cent of total water in soil of cylinder, February 20	25.8	29.2	30.7	32.5	34.6	36.4
Per cent of total water in surface foot on opening cylinder	9.8	5.9	6.7	8.8	5.5	5.6
Per cent of free water in surface foot on opening cylinder	—0.2	—3.3	—2.7	—1.3	—5.2	—6.5
Per cent of total water in 2-6 feet on opening cylinder	7.4	12.6	11.5	23.3	23.7	17.1
Per cent of free water in 2-6 feet on opening cylinder	1.8	3.2	2.1	12.6	12.2	3.1

TABLE 27.—*Free water on opening cylinders with Mexican beans in the experiment of 1911.*

Depth of section		H O Soil	Wauneta	McCook	Holdrege	Hastings	Lincoln
Feet	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	1-4	—4.2	—5.9	—5.6	—5.7	—8.1	—8.7
	5-6	—1.2	—4.2	—3.9	—3.4	—6.6	—8.4
	7-9	1.0	—2.7	—1.9	0.4	—4.6	—6.1
	10-12	3.6	—0.2	0.8	3.6	—1.3	—2.9
2	13-15	3.1	0.2	2.5	4.2	2.0	—2.8
	16-18	1.9	1.6	2.7	4.3	4.2	2.0
	19-21	1.9	2.1	2.7	4.6	5.7	4.8
	22-24	1.8	2.2	2.5	4.5	6.3	5.0
3	25-27	1.8	2.4	1.9	4.6	6.3	5.7
	28-30	1.9	2.5	1.6	6.1	8.5	3.7
	31-33	1.8	2.8	1.4	9.6	10.7	3.6
	34-36	1.8	2.6	1.3	12.3	12.4	2.7
4	37-39	1.9	2.2	1.1	14.2	13.2	3.7
	40-42	1.9	2.4	1.3	14.3	12.6	3.5
	43-45	1.9	2.2	1.2	14.8	13.8	3.3
	46-48	1.9	2.0	1.4	14.6	14.0	3.3
5	49-51	1.9	2.3	1.7	16.0	15.4	3.0
	52-54	1.8	2.7	1.0	16.5	15.3	2.8
	55-57	1.7	3.6	1.7	16.6	15.5	3.1
	58-60	1.7	4.8	2.1	17.2	16.3	2.8
6	61-63	1.6	5.7	2.5	18.9	17.4	2.5
	64-66	1.6	5.9	3.1	18.7	18.0	3.0
	67-69	1.6	6.2	3.8	19.1	18.0	3.0
	70-71	1.6	6.2	4.4	21.1	18.0	3.3
Average	1-12	—0.2	—3.3	—2.7	—1.3	—5.2	—6.5
Average	13-71	1.8	3.1	2.1	12.6	12.2	3.1

In the H O cylinder, which carried four plants from the first planting, the first ripened on April 29, producing 10 beans. Two other plants died during the next few days without having set any seed, and the last plant was dead by May 7, having produced 7 beans. The cylinder was opened on the next day. Roots were abundant thruout the subsoil and the free water in the subsoil was quite uniformly reduced to 1.6 to 1.9 per cent, it being slightly lowest in the sixth foot where fine roots were most numerous. The moisture content of the subsoil was 1.0 to 0.7 per cent below the wilting coefficient.

In the Wauneta cylinder, in which there were three early plants, the first was dead by May 15, producing 6 beans. The second plant was still in healthy condition as late as May 30 but was dead by June 6. From the third plant 3 ripe pods containing 11 beans were removed on May 18. It continued alive and blossomed again before the end of the month. As late as June 6 it was in fair condition, but was found wilted early on the morning of June 7. The next day it appeared quite dead and was removed, but the cylinder was not opened until 15 days later. While some water may have been lost from the surface foot by direct evaporation during these 15 days, it is highly improbable that there was any important movement of water in the subsoil during the interval which elapsed between the harvesting of the last of the crop and the opening of the cylinder.[1] Roots extended to the bottom of the cylinder but were not numerous in the sixth foot. The free water in the subsoil had been reduced quite uniformly to 2 to 3 per cent to a depth of 54 inches; below this it rose gradually to 6.2 per cent. To a depth of 54 inches the moisture had been reduced from 2.0 to 3.0 per cent below the wilting coefficient but in the sixth foot it was about 2.0 per cent above the wilting coefficient.

In the McCook cylinder, in which there were three late plants, one on June 6 ripened a pod containing 2 beans. This plant, however, as well as the two others continued green but made no growth. By July 18 all had died without forming any more seed. The cylinder was opened that day. Roots extended to the bottom of the cylinder and were abundant thruout the first five feet. The free moisture in the upper four feet of subsoil had been quite uniformly reduced to 1.0 to 2.0 per cent. In the sixth foot there was still 3.4 per cent.

In the Holdrege cylinder the single surviving plant, from the first planting, ripened on May 18, producing 9 beans in two pods. Roots extended to the upper portion of the sixth foot but they had drawn very lightly on the moisture in the subsoil below the third foot, there being from 14 to 20 per cent of free water in the lower sections. Only in the first and second feet was the moisture reduced to the wilting coefficient.

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[1] Alway, F. J., and Clark, V. L., *loc. cit.*

In the Hastings cylinder, which carried one early plant and two late plants, the first ripened May 18, producing a single bean. On May 30 one of the remaining plants was in blossom but on June 6 both plants were dead. The cylinder was opened 16 days later. In the distribution of roots and in the moisture conditions this very closely resembled the Holdrege cylinder.

The single plant in the Lincoln cylinder ripened two pods with 5 beans on May 11. It continued green and blossomed again from May 18 to June 8, but was dead by June 27 without having formed any more pods. The cylinder was opened on that day. Roots were quite abundant to the bottom of the cylinder, but not in nearly the quantity found in the H O cylinder. The moisture of the subsoil, except in parts of the second and third foot, where fine roots were not numerous, was reduced quite uniformly to 2.5 to 3.7 per cent of free water, or to 2.0 to 3.0 per cent below the wilting coefficient. (Figure 27.)

The crevice between soil column and cylinder wall was entirely wanting in the H O cylinder and reached to only 5 and 6 inches respectively in the Wauneta and McCook cylinders, to 27 and 18 inches respectively in the Holdrege and Hastings cylinders, and in all cases was very small. In the Lincoln cylinder it extended to 18 inches.

MAIZE.

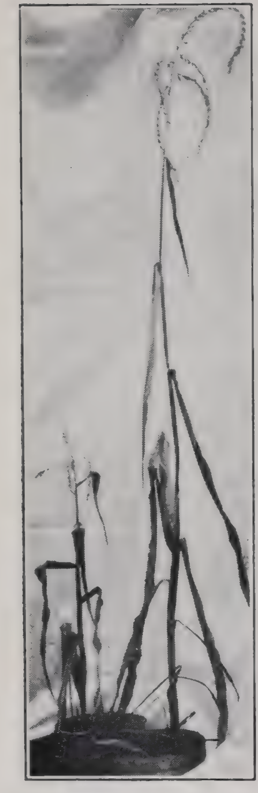
Four germinated kernels of a white flint variety obtained from the Sulphur Spring Valley Dry Farm were planted on February 20 in each of two cylinders, Nos. 24 and 76, which had been filled with H O surface soil and H O subsoil as described on pages 80 and 81. Four days later all the plants were up, and at the end of another week they were thinned to the most vigorous one in each cylinder. The two plants did well until the latter part of March, when the one in No. 76 from some unknown cause received a severe check.

On April 11 that in No. 24 was in bloom and the next day the silk appeared. On April 29 the plant was 54 inches high and had 7 leaves. On May 18 all the leaves were dead, and 12 days later the plant, then quite dry, was harvested and the cylinder opened. The plant had formed a very small ear bearing 13 kernels.

The plant in cylinder No. 76 recovered somewhat during April, and on the 29th of that month was 23 inches high. It had already been in tassel two weeks but the silk did not appear until May 6, before which time all the pollen had fallen. All of the plant except the ear had dried up by May 18 but this was still green when the cylinder was opened on May 30.

TABLE 28.—*Data on experiment with maize and mesquite in 1911.*

	Maize		Mesquite
	Cylinder 24	Cylinder 76	Cylinder 23
Weight of dry soil in cylinder, in grams	47,258	45,614	46,947
Weight of water in soil at planting time, in grams	11,254	11,198	10,989
Weight of water in soil on opening cylinder, in grams	3,308	6,933	2,253
Weight of water lost, in grams	7,946	4,265	8,736
Time from planting seed to death of plant, in days	99	99	142
Weight of seed, air-dry, in grams	2.70	....	....
Weight of crop, dried at 110° C., in grams	14.38	5.1	7.1
Weight of water lost per gram of crop, dried at 110° C., in grams	553	836	1,230
Weight of roots, at 110° C., in 1st foot, in grams	0.548	0.079	1.672
Weight of roots, at 110° C., in 2d foot, in grams	0.084	0.070	0.382
Weight of roots, at 110° C., in 3d foot, in grams	0.071	0.019	0.307
Weight of roots, at 110° C., in 4th foot, in grams	0.139	0.003	0.243
Weight of roots, at 110° C., in 5th foot, in grams	0.203	0.002	0.320
Weight of roots, at 110° C., in 6th foot, in grams	0.532	0.008	0.590
Total weight of roots in the 6 feet, in grams	1.577	0.181	3.514
Total weight of roots below the first foot, in grams	1.029	0.102	1.842
Date of death of plant	May 30	May 30	July 12
Date of opening cylinder	May 30	May 30	July 12
Per cent of total water in soil, February 20	24.3	25.1	22.8
Per cent of total water in surface foot on opening cylinder	7.5	6.7	4.5
Per cent of free water in surface foot on opening cylinder	—2.5	—3.3	—5.5
Per cent of total water in 2–6 feet on opening cylinder	6.9	16.9	4.9
Per cent of free water in 2–6 feet on opening cylinder	1.3	11.3	—0.7



No. 76. No. 24.

Fig. 33. Corn plants 96 days after planting. Both dead.

Figure 33 shows the plants as they appeared on May 27. The relation of the distribution of water to the root development is shown in figure 34 and Table 29.

In neither cylinder had a crevice formed between the soil column and the cylinder wall.

In the first cylinder roots were abundant thruout the soil mass, reaching to the very bottom of the cylinder, while in the other they were numerous in the first two feet of subsoil and very scarce in the three feet below.

In No. 24 the free moisture amounted to about 1.5 per cent at all depths below the first foot while in No. 76 it rose steadily from 1.3 per cent in the upper part of the second foot to over 18.0 per cent at the bottom of the cylinder. The water in the first had been reduced to 1.0 per cent below the wilting coefficient but that in the other was still far above the wilting coefficient. (Figure 22.)

SUMMARY OF EXPERIMENT OF 1911.

When the seeds were planted, the cylinders carried from one and a half to three times as much free water as the same soils would have retained under field conditions. Abnormally high temperatures near the close of the experiment hastened the death of the wheat and bean plants, which in general had poorly developed root systems. Normal milo and bean plants were produced on most of the soils, but all the wheat plants failed to make a normal growth and died while an abundance of free water still remained in the subsoil. In one cylinder a maize plant developed roots to the bottom of the cylinder and uniformly reduced the water content to a point below the wilting coefficient.

In nearly all the cylinders roots penetrated to the bottom but in the case of the wheat and the beans the development was in most cases much less than in the preceding two experiments. Where roots were developed in abundance the water content was reduced almost to the hygroscopic coefficient before the plants died.

TABLE 29.—*Moisture conditions in cylinders with maize.*

Depth of section		Free water	
		Cyl. 24	Cyl. 76
Feet	*Inches*	*Per cent*	*Per cent*
1	1-4	—5.7	—5.8
	5-6	—3.8	—4.4
	7-9	—1.4	—2.6
	10-12	0.6	—0.5
2	13-15	1.3	1.3
	16-18	1.2	3.1
	19-21	1.4	5.9
	22-24	1.5	6.9
3	25-27	1.5	7.6
	28-30	1.6	8.3
	31-33	1.4	9.0
	34-36	1.3	9.5
4	37-39	1.4	10.1
	40-42	1.4	10.6
	43-45	1.4	11.6
	46-48	1.3	13.0
5	49-51	1.5	12.7
	52-54	1.4	13.8
	55-57	1.4	14.9
	58-60	1.4	16.5
6	61-63	1.4	16.3
	64-66	1.4	17.9
	67-69	1.1	18.9
	70-71	1.0	18.4
Average	1-12	—2.5	—3.3
Average	13-71	1.3	11.3

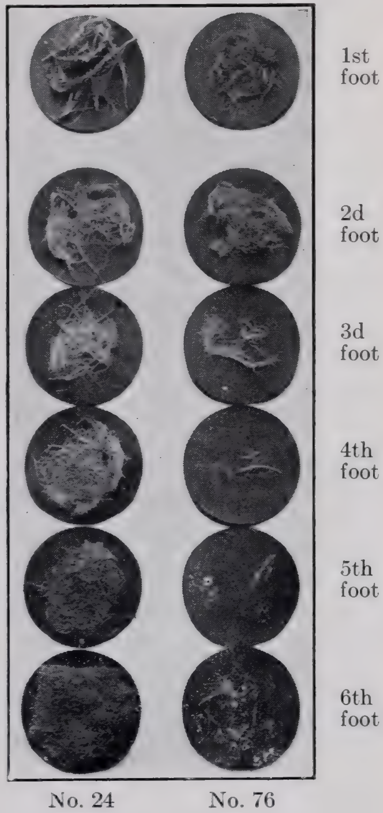


Fig. 34. Roots of corn.

The branching of the milo plants favored the exhaustion of the soil moisture by greatly reducing the transpiring surface after the root system had been fully developed and the moisture content much reduced.

Little difference in the growth of plants and in the development of roots was observed between the most westerly loess soil—from Wauneta—and the neighboring residual High Plains soil from Madrid.

Except in the case of those from the most easterly of the five localities on the loess, no difference was observed in the readiness with which roots penetrated the soils or in the extent to which the free water could be exhausted, the latter probably being dependent upon the former. The eastern soils, which gave up their free water least completely, were much less calcareous than the others.

In all the cylinders a hard crust developed below the mulch.

EXPERIMENTS WITH PERENNIAL DESERT LEGUMES.

Three species were employed more or less, viz, *Prosopis velutina* (Mesquite), *Acacia Greggi* (Catsclaw), and *Acacia constricta*. The seeds of the first two were gathered near Benson, Arizona, and those of the last near Columbus, New Mexico. Both places are in desert regions, the normal annual precipitation being a little under 10 inches.

The seeds were planted on December 31, 1910, in small flowerpots filled with surface soil from the Experiment Station farm. Later, part were transferred to larger flowerpots filled with the same soil. Until they were transplanted to the metal cylinder and left to die all were watered freely.

Experiment 1.—In this there were used two cylinders of galvanized iron 6 inches in diameter and 1 foot high, in the bottom of each of which ten small holes had been punched. In the bottom of each a layer of coarse gravel $\frac{3}{4}$ of an inch in thickness was placed and then H O subsoil tamped in to within 3 inches of the top. On February 4, 1911, one small mesquite plant (*Prosopis velutina*) was transplanted, soil and all, to each cylinder. The space between the black soil and the cylinder was filled with H O subsoil. The surface was covered with a one-half inch mulch of coarse sand, the top of this being one-half inch below the top of the cylinder. Then the soil was thoroly saturated and the cylinders left in the greenhouse without further addition of water and without any protection from the sun's rays.

The mesquites when transplanted were 4 inches high and bore 7 and 9 compound leaves, respectively. On March 18 the plants were both 10.5 inches high and bore 15 and 14 compound leaves, respectively; even on this date some of the lowest leaves had fallen from each. On April 11 the tip of the plant in cylinder No. 3 was dead and only 6 compound leaves remained, while the tip of the plant in cylinder No. 4 was still alive altho the number of compound leaves on it also was only 6. Nine days later the numbers of leaves were 4 and 6 respectively. On May 7, just before No. 3 was opened, when the plants were photographed (fig. 35), the numbers of compound leaves were 1 and 5 respectively and the tip of the plant in No. 4 was dead. On May 15, when No. 4 was opened, the plant in it carried 4 leaves.

Roots had penetrated the whole of the soil mass. For moisture determinations, only the most protected portion of the H O subsoil in each was used. All of the black soil and the 2 inches of subsoil below this, as well as the lowest 2 inches of the soil column and the 1 inch of the soil column next the cylinder wall, were removed and the remaining portion of the soil column, which was about 5 inches high and 4 inches in diameter, was well mixed and moisture determinations made in triplicate. The free water content in this soil portion from cylinder No. 3 was —0.8 per cent and in that from No. 4 was —0.6 per cent.

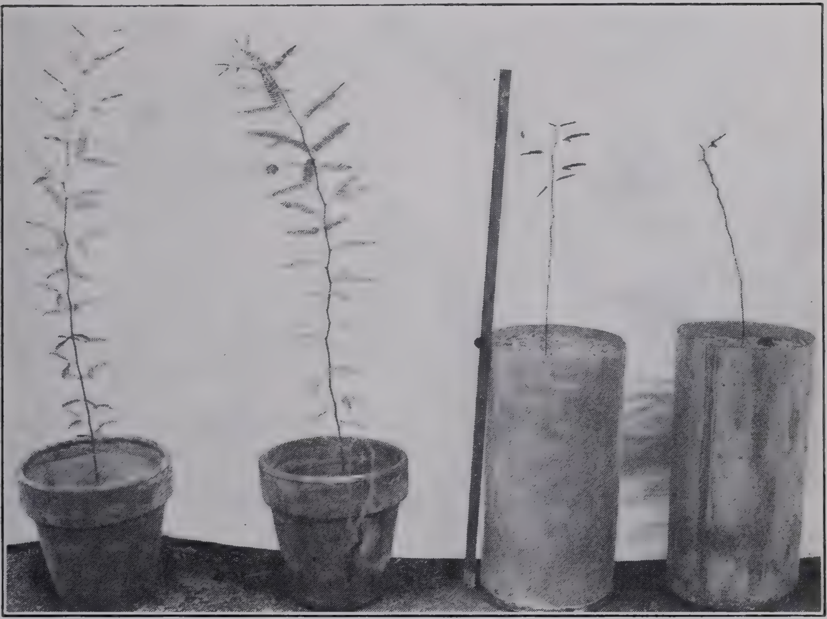


Fig. 35. Mesquite plants of the same age. The two on the left had been watered freely while the other two had not been watered for 92 days. Altho no free water remained in the soil of the latter two cylinders,—even in the most protected portions,—both plants were alive.

In figure 35 are shown the mesquite plants as they appeared on May 7, together with two others which had been transplanted at the same time as those in Nos. 3 and 4, but to large flowerpots, afterwards being watered daily. On May 7 each of the latter was about 26 inches high and bore about 30 compound leaves.

Experiment 2.—In this a 6-foot cylinder filled with H O surface soil and H O subsoil was used. It had been filled and saturated along with those described on pages 80 and 81. On February 28, 1911, two mesquite plants were placed in this. In transplanting the mesquites the surface soil was removed to a depth of 6 inches and the whole of the soil from the two flowerpots introduced so as not to disturb the roots of the mesquites, after which the open spaces were filled with the H O surface soil which had just been removed. A day mulch of H O surface soil was then added. Thus there was some Lincoln surface soil in the first 6 inches of this cylinder but the quantity was small and its relative hygroscopicity was so similar to that of the H O surface soil that it might be considered as part of the latter.

The larger of the two plants grew much the more rapidly, but both did well until early in April, when the smaller began dying. The latter gradually declined until on June 6 it appeared quite dead. Its height was 14.5 inches. The other continued to grow until it was 47.5 inches high; then it began to drop its leaves, one by one, but on June 17 it still appeared quite vigorous. At the end of June it had lost most of its leaves and on the evening of July 5, a day when the maximum temperature in the greenhouse reached 130° F., it appeared to have been killed. On July 12, the plant being quite dry, it was removed and the cylinder opened. About a dozen leaves remained on the plant when it died.

A small crevice extended to the 9th inch but there was none below. Roots were well distributed thruout the subsoil. (See Table 28 and figure 36.)

The subsoil, as shown in Table 30 and in figure 22, was very dry, the moisture content being uniform and distinctly below the hygroscopic coefficient. There can be little doubt but that some little time before the death of the larger plant all free moisture had disappeared from both soil and subsoil. Under more favorable temperature conditions it would probably have continued to live for some time, notwithstanding the entire absence of free moisture, dropping its leaves one by one. Instead of continuing to thus drop its leaves until all were gone it had died with a dozen still adhering. The temperature in the shade in the open air on that day was 110° F., while the maximum thermometer in the greenhouse recorded a temperature of 130° F. That it was not the high temperature, independent of the transpiration, which killed the plant is evident from the circumstance that various other mesquites and acacias, which were in the same greenhouse but which were watered daily, remained uninjured. Even two milo plants, those in the McCook and Holdrege cylinders, survived (pages 94 and 95).

TABLE 30.—*Moisture conditions at death of mesquite.*

Depth of section		Total water	Free water
Feet	*Inches*	*Per cent*	*Per cent*
1	1-4	2.7	—7.3
	5-6	4.0	—6.0
	7-9	5.1	—4.9
	10-12	6.3	—3.7
2	13-15	4.5	—1.1
	16-18	4.7	—0.9
	19-21	5.0	—0.6
	22-24	4.9	—0.7
3	25-27	5.0	—0.6
	28-30	4.8	—0.8
	31-33	5.0	—0.6
	34-36	4.8	—0.8
4	37-39	4.9	—0.7
	40-42	4.8	—0.8
	43-45	4.7	—0.9
	46-48	5.0	—0.6
5	49-51	4.9	—0.7
	52-54	5.0	—0.6
	55-57	5.0	—0.6
	58-60	5.0	—0.6
6	61-63	5.0	—0.6
	64-66	5.0	—0.6
	67-69	5.0	—0.6
	70-71	4.9	—0.7
Average	1-12	4.5	—5.5
Average	13-71	4.9	—0.7

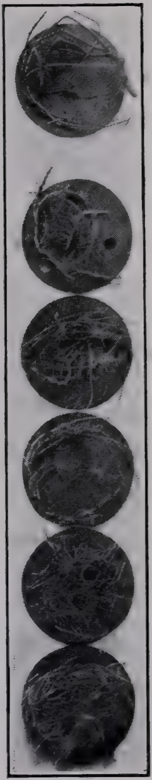


Fig. 36.

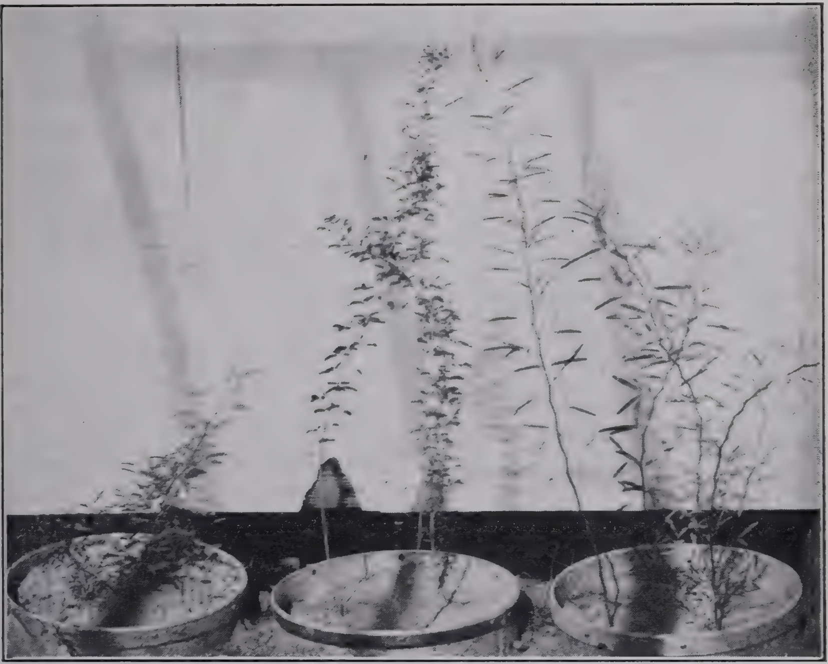
Roots of mesquites.

EXPERIMENT 3.—In this experiment three water-tight cylinders, each two feet high and one foot in diameter, were used. The young plants were transferred from the flowerpots on June 17. 1911, they being nearly 6 months old. The soil used was H O subsoil except for the small amount of Lincoln surface soil from the small flowerpots, this having been transferred so as not to disturb the roots. A large supply of H O subsoil had been brought to a content of about 14 per cent of total water and with this the cylinders were filled, with tamping, to a height of 18 inches

TABLE 31.—*Rate of loss of water from cylinders carrying desert legumes*

	I	II	III
Weight of empty cylinder, in grams	3,630	3,400	3,630
Weight of cylinder with soil, June 17, in grams	69,400	69,630	70,330
Weight of cylinder with soil, August 11, in grams	64,410	65,200	66,330
Weight of cylinder with soil, August 26, in grams	64,210	64,690	65,590
Weight of cylinder with soil, September 2, in grams	64,100	64,380	65,330
Weight of cylinder with soil, September 16, in grams	64,010	64,350	65,190
Weight of cylinder with soil, September 23, in grams	63,960	64,210	65,020
Weight of cylinder with soil, September 30, in grams	....	64,290	65,050
Weight of cylinder with soil, October 6, in grams	....	64,180	65,020
Weight of cylinder with soil, October 13, in grams	....	64,150	65.020
Weight of soil, dried at 110° C., in grams	57,833	58,172	58,598
Weight of water in soil of cylinder, June 17, in grams	7,937	8,058	8,102
Per cent of water in soil of cylinder, June 17, in grams	13.7	13.8	13.8
Per cent of water in soil of cylinder, August 11, in grams	5.1	6.2	7.0
Per cent of water in soil of cylinder, August 26, in grams	4.7	5.3	5.7
Per cent of water in soil of cylinder, September 2, in grams	4.6	4.8	5.3
Per cent of water in soil of cylinder, September 16, in grams	4.4	4.8	5.0
Per cent of water in soil of cylinder. September 23, in grams	4.3	4.5	4.7
Per cent of water in soil of cylinder, September 30, in grams	.	4.7	4.8
Per cent of water in soil of cylinder, October 6, in grams	..	4.5	4.7
Per cent of water in soil of cylinder, October 13, in grams		4.4	4.7

from the bottom. The leguminous plants were transferred, soil and all, and placed on this subsoil. Then more of the moist H O subsoil was packed firmly around and on the top of the transferred black soil. Then the whole was covered with two inches of air-dry H O subsoil. After the transplanting the cylinders were kept in a cool, partly shaded room until July 6, when they were so placed in a pit in the greenhouse that the tops of the cylinders projected from two to three inches above the level of the ground. No water was added. The plants showed no sign of injury from the transfer and afterwards all made considerable growth.



III *Prosopis velutina* and *Acacia constricta*

II *Acacia Greggi*

I *Prosopis velutina*

Fig. 37. Desert legumes in 2-foot cylinders when growth had ceased.

The three cylinders carried the following:

I. Three plants of *Prosopis velutina.*

II. Four plants of *Acacia Greggi.*

III. Three plants of *Prosopis velutina* and one plant of *Acacia constricta.*

The first sign of injury was observed early in August in the case of I, and on August 11 the tips of all branches on the plants in this were dead and the lowest leaves had begun falling. In II and III, on the same date, the tips were uninjured and no leaves had fallen. Growth had ceased in I and II by August 15, when the photograph (figure 37) was taken, and in III by September 1.

On August 16 the tallest plant in I was in the worst condition, while many leaves had fallen from the second plant and a few from the third. In II all the tips were dead and the lowest leaves had fallen. In III none of the plants was yet injured.

Cylinder I was opened on September 23 and the other two were opened on October 13. In none were all the plants dead when the cylinders were opened but in the case of each all the tips had died and nearly all the leaves had fallen; the most vigorous plant in each retained only from five to seven compound leaves.

The cylinders were weighed on June 17, after the plants had been placed in them, and again on August 17 after the first signs of injury from drouth were noticed. After the latter date they were weighed at intervals until opened, using scales sensitive to 15 grams. During the three weeks preceding the opening of cylinders II and III the loss in weight was practically nothing, while during one week, September 23 to 30, there was a slight gain in weight. This week was characterized by cloudiness and unusually high humidity of the air, and the increase in weight is to be attributed to the increase in the amount of hygroscopic moisture in the dry surface mulch. Table 31 shows the loss in weight of the cylinders and the average per cent of water in the soil of the different cylinders. The weights of the plants are included in those of the soil, but the former were too small to appreciably affect the results.

In none of the cylinders did a crevice form between cylinder wall and soil column. The roots penetrated to the bottom of the cylinders, being most abundant in the lowest three-inch section. The moisture conditions existing at the time of opening the cylinders are shown in Table 32. Free water had entirely disappeared. Below the first foot the moisture content was practically uniform. The black surface soil, in which the plants had been started and which was transferred with these, appears, from the mere statement of the amount of free water, to be drier than the contiguous subsoil, but in reality it is not, both being about half saturated with hygroscopic moisture. This black soil was present in the form of three or four conical masses surrounded entirely by H O subsoil.

Summary of experiments.—The plants remained alive after the water content had fallen slightly, but distinctly, below the hygroscopic coefficient and even to a point at which the milo had died. When conditions were favorable they adjusted themselves to the gradually increasing difficulty of absorbing water, due to the soil steadily becoming drier, by dropping their leaves one by one, transpiration finally almost ceasing. When, however, conditions causing an abnormally high transpiration suddenly set in, the plants died without dropping their leaves.

TABLE 32.—*Moisture conditions in cylinders carrying desert legumes.*

Depth of section	Total water			Free water		
	I	II	III	I	II	III
Inches	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1-3	2.6	2.2	2.2	—3.0	—3.4	—3.4
4-6	2.8	2.7	3.0	—2.8	—2.9	—2.6
7-9	3.6	3.8	4.0	—2.0	—1.8	—1.6
10-12	4.3	4.6	4.4	—1.3	—1.0	—1.2
13-15	4.8	4.8	5.1	—0.8	—0.8	—0.5
16-18	4.9	5.0	5.2	—0.7	—0.6	—0.4
19-21	4.9	5.0	5.3	—0.7	—0.6	—0.3
22-24	4.8	5.0	5.2	—0.8	—0.6	—0.4
Black soil*........	5.7	6.0	5.3	—5.6	—5.3	—6.0

* This was between the 4th and the 9th inches and was entirely surrounded by H O Subsoil.

The experiments furnish no evidence of any ability on the part of these legumes to utilize *for growth* the last portion of free water, but they indicate that this portion has a very high value for the maintenance of life and that even some of the water below the hygroscopic coefficient may be *available for the maintenance of life* in these plants.

This evident ability of these desert plants to make use of water below the hygroscopic coefficient suggests that the absolute limit of soil water available for either growth or the maintenance of life may be the *hygroscopicity* as defined by Rodewald and Mitscherlich.[1]

THE HYGROSCOPIC COEFFICIENT VERSUS THE WILTING COEFFICIENT IN COMPARISONS OF THE AVAILABLE MOISTURE OF SOILS.

The free moisture in semiarid and arid soils, in so far as the above-described experiments and the results of unpublished field studies permit conclusions to be drawn, appears to be capable of more complete exhaustion by plant roots before the plants die than does that in humid soils. This may be due simply to the more complete penetration of the soil mass by the roots in the case of the semiarid and arid soils, and this in turn be due to the flocculation of the clay in the latter. It is well known that the arid and semiarid soils are strongly calcareous compared with humid soils, a good illustration being furnished by the loess soils of the Transition Region.[1]

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[1] Rodewald, H., and Mitscherlich, A. Die Bestimmung der Hygroskopizität. Landwirthschaftlichen Versuchs-Station, 1904, vol. 59, pp. 433-441.

Briggs and Shantz[2] consider that a statement of the free water may be very misleading in comparisons of the available moisture in soils. The most of the experiments described above furnish little or no evidence as to the correctness of these views, the cylinders in most cases not having been opened until long after growth of the contained plants had ceased. The few exceptions include cylinders I and IV with wheat in 1909 and cylinders I and II with beans in 1910. The former ripened seed normally and as soon as the plants appeared quite ripe the cylinders were opened; in both the moisture of the subsoil had been quite uniformly reduced to more than 2 per cent below the wilting coefficient. Much the same was true for the two cylinders with beans in 1910.

Some evidence is furnished by the numerous cylinders in which when the plants died the moisture content of the upper portion of the subsoil, where roots were the most numerous, was much below the wilting coefficient while that of the lower portion, where the roots, altho much less abundant, were still present, was much above the wilting coefficient. This would indicate that when once the roots are developed in the subsoil they fail to distinguish sharply between the portion of the free water above the wilting coefficient and the portion below; otherwise, after the moisture in a portion of the subsoil had been reduced to the wilting coefficient, water removal from this portion would cease so long as roots of the same plant were in contact with subsoil with a moisture content above the wilting coefficient. It seems that in reality the roots in the drier portions of the subsoil may be removing "water nonavailable for growth" at the same time that roots of the same plant in moist subsoil are removing "water available for growth."

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[1] Alway, F. J. Composition of the Loess Soils of the Transition Region, Eighth International Congress of Applied Chemistry, 1912, Report of Section VII, p. 11.

[2] They have incorrectly stated the writer's earlier views as to the basis for comparing the available moisture in soils. They state: "In the absence of a more definite relationship between the wilting coefficient and the hygroscopic coefficient, Alway has advocated deducting the hygroscopic coefficient from the field soil-moisture determinations as a basis for comparing the available moisture in soils." (Bul. 230, Bureau of Plant Industry, p. 66.) On the contrary the writer had stated that the "free water," obtained by deducting the hygroscopic coefficient from the total water (= field moisture determination), "does not indicate the amount of water that is available in such form that the plant can continue a normal growth. * * * It is probable that the normal growth ceases when the percentage of free moisture falls to from 4 to 8 per cent according to the soil." (Bul. 130, Bureau of Plant Industry, p. 38.) "A comparison of the fields on the basis of the amount of free water in the first six feet assumes that a definite value is to be attached to a certain percentage of free water, independent of the kind of soil * * * in which it occurs. It is evident from Hilgard's work, however, that a higher percentage of free moisture is required on clay than on sandy soils in order that plant growth may continue. * * * It has been assumed that the lower limit of free moisture in the boulder clay is 4.5 and in the lacustral clay 6.0 per cent. The free water less this 4.5 or 6.0 per cent is for convenience at present designated the 'x water.'" (Jour. Agr. Sc., vol. 2, pp. 338-340.) In the earlier publication this "x water" had been referred to as "water probably available for normal plant growth." (Bul. 130, Bureau of Plant Industry, p. 37.)

Even if the soil moisture supply is so low that no growth can take place, it may suffice for the maturing of some seed, as with a wheat crop, or for the maintenance of life in the case of perennials. With the latter the mere maintenance of life thru a very dry period may be far more important than any growth in that particular year, as in the case of orchards, hedges, and even alfalfa fields. A slight difference in the ability of a perennial plant to make use of the last portion of the free water may determine whether or not it is adapted to extremely severe conditions.

As an illustration of the relative value of the two coefficients in comparisons of available moisture in field studies the data in Tables 33 to 36 are presented. The field referred to in Table 33 is on the farm of Hon. George Coupland near Elgin, Nebraska. It had been in alfalfa for ten years and at the time of sampling there was still a fair stand of healthy plants. The water-table was probably at a depth of 45 to 50 feet below the surface of the field, the soil of which consists of loess to a depth of 35 feet. The alfalfa field referred to in Table 34 is adjacent to the Nebraska Experiment Station farm. It had been in alfalfa for five or six years and, judging from its vigorous growth during prolonged drouths, the alfalfa plants derived much water from the water-table, which at the time of sampling was between 11 and 12 feet below the surface. The locust grove (Table 35) is on the H O Ranch near Madrid, in western Nebraska. At the time the samples were taken it had passed thru a drouth remarkable both for its duration and for its severity. All the trees, altho not in leaf at the time, were alive, as evidenced by their still being alive a year later. The abandoned olive orchard referred to in Table 36 is near Casa Grande, Arizona, and has been described by Mason.[1] The samples were taken by the writer from a trench excavated at the base of an olive tree beside which was growing a mesquite. The former was about 18 years old, and the latter, judging from the number of annual rings, was 11 or 12 years old. The roots of the olive did not extend more than 3 feet below the surface, but the tap-root of the mesquite extended below the sixth foot. On the day before the samples were taken a rain of 0.70 inch had fallen.

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[1] Mason, S. C. Drought Resistance of the Olive in the Southwestern States. Bul. 192, Bureau of Plant Industry, U. S. Dept. of Agriculture 1911, p. 13.

In the case of the two alfalfa fields the plants were growing normally and in the one the roots were evidently deriving much of their water from the water-table. However, in both cases the moisture of the subsoil to a considerable depth had been reduced

TABLE 33.—*Moisture conditions in an old alfalfa field near Elgin, Nebraska, August 24, 1911.*

Depth in feet	Total water	Hygroscopic coefficient	Wilting coefficient	Free water	"Water available for growth"
	Per cent			*Per cent*	*Per cent*
1	12.4	8.3	12.2	4.1	0.2
2 to 6	11.5	9.3	13.7	2.2	—2.2
7 to 12	11.7	10.2	15.0	1.5	—3.3
13 to 18	12.8	10.1	14.8	2.7	—2.0
19 to 24	13.1	9.9	14.5	3.2	—1.4
25 to 27	13.6	10.3	15.2	3.3	—1.6
28 to 30	15.6	10.1	14.8	5.5	0.8
31	18.1	10.3	15.2	7.8	2.9
32	20.1	10.5	15.4	9.6	4.7
33	20.2	10.0	14.7	10.2	5.5
34	21.1	10.0	14.7	11.1	6.4
35	19.9	9.5	14.0	10.4	5.9
36	12.6	4.7	6.9	7.9	5.7

TABLE 34.—*Moisture conditions in a naturally subirrigated alfalfa field near the Nebraska Experiment Station farm, August 4, 1911. The water-table was about 12 feet below the surface.*

Depth in feet	Total water	Hygroscopic coefficient	Wilting coefficient	Free water	"Water available for growth"
	Per cent			*Per cent*	*Per cent*
1	10.8	9.7	14.3	1.1	—3.5
2 to 4	13.0	9.4	13.8	3.6	—0.8
5 to 6	14.1	11.6	17.0	2.5	—2.9
7 to 8	22.0	13.7	20.2	8.3	1.8
9	25.6	13.3	19.6	12.3	6.0
10	25.7	11.0	16.2	14.7	9.5
11	26.5	11.5	16.9	15.0	9.6

TABLE 35.—*Moisture conditions in a young locust grove near Madrid, Nebraska, on April 20, 1911.*

Depth in feet	Total water	Hygroscopic coefficient	Wilting coefficient	Free water	"Water available for growth"
	Per cent			*Per cent*	*Per cent*
1	13.7	9.8	14.4	3.9	—0.7
2	11.8	10.5	15.4	1.3	—3.6
3	10.4	8.2	12.0	2.2	—1.6
4	9.8	7.5	11.0	2.3	—1.2
5	8.5	7.0	10.3	1.5	—1.8
6	7.9	7.2	10.5	0.7	—2.6
7	8.0	7.3	10.7	0.7	—2.7
8	8.1	7.1	10.4	1.0	—2.3
9	8.3	6.7	9.8	1.6	—1.5

TABLE 36.—*Moisture conditions in an abandoned olive orchard near Casa Grande, Arizona, October 6, 1911.*

Depth	Total water	Hygroscopic coefficient	Wilting coefficient	Free water	"Water available for growth"
	Per cent			*Per cent*	*Per cent*
1 to 4 in.	10.3	6.0	8.8	4.3	1.5
7 to 12 in.	6.2	6.9	10.1	—0.7	—3.9
13 to 18 in.	6.8	7.2	10.6	—0.4	—3.8
19 to 24 in.	8.5	9.0	13.2	—0.5	—4.7
3d foot	13.4	13.8	20.2	—0.4	—6.8
4th foot	9.3	10.6	15.6	—1.3	—6.3
5th foot	7.8	8.1	11.9	—0.3	—4.1
6th foot	6.9	7.5	10.0	—0.6	—3.1

below the wilting coefficient. In the other two instances trees were alive while their roots occupied subsoil with a moisture content much below the wilting coefficient.

SUMMARY AND CONCLUSIONS.

Water-tight cylinders, 6 feet long and holding about 100 pounds of soil, were either filled with dry soil, saturated with water, and drained before sealing at the bottom, or filled with soil already containing the desired amount of moisture. These were removed to a greenhouse, seeds of wheat, milo, beans, or maize planted in the moist surface soil, and no more water added, the resulting plants being allowed to grow until they matured normally or died. Upon the death of all the plants in a cylinder it was opened, both the total and the free water in each 3-inch section of soil determined, and the distribution of roots observed. In other cylinders three perennial desert legumes were grown until they died or were near their limit of endurance; then the cylinders were opened and the moisture content and root distribution determined.

In all the cylinders bearing plants, a hard crust developed below the surface mulch of dry soil but it seemed to have no injurious effect. The formation of such a crust is to be regarded as unavoidable where during a prolonged period of rainless weather plants with a well-developed root system and a very limited amount of moisture in the subsoil are transpiring a large amount of water.

In their ability to exhaust the moisture of the subsoil before dying, Red Fife wheat, Kubanka wheat, milo, Mexican beans, and maize showed little difference, but in their ability to continue alive after first showing serious injury from drouth they exhibited marked differences. The interval between wilting and death in the case of the beans amounted to only a few days but in that of wheat and milo it often extended to many weeks. Where there was a well-developed root system and no remarkably unfavorable conditions occurred before the death of the plants, the moisture content could be reduced by any of these plants almost to the hygroscopic coefficient.

In experiments with perennial desert legumes the plants remained alive after the water content had fallen slightly, but distinctly, below the hygroscopic coefficient, even to the point at which all the above-mentioned annual crop plants had died. Under favorable conditions these legumes adjusted themselves to the gradually increasing dryness of the soil by dropping their leaves one by one, but where, with the subsoil moisture already reduced to near the hygroscopic coefficient, conditions causing an abnormally high transpiration suddenly set in, death occurred without the leaves having dropped. While the experiments furnish no evidence of any ability on the part of these legumes to utilize *for growth* the last portion of free water, they indicate that this portion has a very high value for the maintenance of life and that even some of the water below the hygroscopic coefficient may be available for the maintenance of life in these plants.

In the portions of a semiarid subsoil where roots are well developed the final content of free water is independent of the distance from the surface, except where the stored water is much in excess of the amount required for the complete maturity of the plant.

When the portion of the subsoil in immediate contact with the roots contains only a comparatively small amount of free water, crop plants may die quickly if conditions are such as to cause an unusually rapid transpiration. An abundance of free water in deeper portions of the subsoil, into which but few roots have been developed, may not avail to carry the plant over such a critical period.

The economy in the use of a certain amount of free water stored in the subsoil may be much affected by its distribution. A high content confined to the portion of the soil near the surface may induce a rapid growth of the plants and an economical use of the water in so far as the production of foliage alone is concerned, but the resulting large transpiring surface may cause the death of the plants before they reach maturity. The same amount of free water distributed thru a greater depth may induce a slower growth, allow a longer lease of life, and so permit of the production of seed, while if the same amount be distributed thru a still greater depth the content of free water may everywhere be too low to permit of the development of roots, thus rendering the free water nonavailable.

The loss of water from the subsoil of dry lands under crop seems to take place almost entirely thru transpiration. In the absence of plants the loss from the subsoil is small. The stored moisture of the different depths of subsoil in the field becomes available to the plants by the roots being developed into these depths, but little moisture being elevated to the roots by capillarity. However, in the case of subsoils saturated in cylinders or pots and comparable to such field subsoils as are only a few feet above the water-table, the content of free water is so high that large amounts of moisture may be elevated to the roots by capillarity. The amount of water retained by a soil saturated in pots or cylinders is far in excess of the amount retained by a similar soil saturated in a field where the water-table is at a considerable depth below the surface, as in ordinary dry-land soils.

To obtain a basis for comparing the available moisture in soils, either the hygroscopic coefficient or the wilting coefficient may be used. In general the one may prove as satisfactory as the other, but in considering the germination of seeds and the development of roots, and hence the whole of the earlier portion of the life of annual crop plants, the wilting coefficient appears the preferable; while in considering the production of seed in the case of annual crop plants, and the maintenance of life and even the growth of perennial plants, the hygroscopic coefficient appears much the preferable.

In the case of ordinary dry-land soils, the water-table being at a considerable depth below the surface, the *maximum* amount of soil water available to plants, for growth and for the maintenance of life, is *approximately* equal to the *free water*—the difference between the total water and the hygroscopic coefficient —in those portions of the soil and the subsoil occupied by the roots. For some plants the available water appears to be somewhat greater and for others somewhat less than the free water.

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BULLETIN
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THE INHERITANCE OF A RECURRING SOMATIC VARIATION IN VARIEGATED EARS OF MAIZE

BY R. A. EMERSON

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CONTENTS

PAGE
Introduction 5
De Vries's studies of *Antirrhinum* 7
Correns's studies of *Mirabilis* 8

Results of experiments with maize.

F_1 from red, striped, and white seeds of variegated P_1 9
F_2 and F_3 from red-eared F_1 plants 17
Non-inherited somatic variations 20

Interpretation of results.

Hypothesis of genetic-factor modifications in relation to the inheritance of somatic variations 21

Factorial analysis of results with maize.

P_1 and F_1 generations 23
F_2 and F_3 generations 26
Comparison of results from *Mirabilis, Antirrhinum* and *Zea* 28

General considerations.

Factor modifications and heterozygosis 30
Factor modifications at different stages in the development of the plant 32
Nature of variegation-factors 33
Summary 34

THE INHERITANCE OF A RECURRING SOMATIC VARIATION IN VARIEGATED EARS OF MAIZE[1]

By R. A. EMERSON

Introduction

The inheritance of variegation has special interest and importance in genetics. It is with forms of variegation that the only two certainly known cases of non-Mendelian inheritance have had to do. I refer to Baur's experiments with *Pelargonium,* in which crosses of green-leaved and white-leaved forms exhibited somatic segregations in F_1 that bred true in later generations, and to Correns's work with *Mirabilis,* which showed green and white leaf color, to be inherited through the mother only. De Vries's conception of "ever-sporting" varieties was apparently founded largely upon the behavior of variegated flowers in pedigree cultures, from which he reached the conclusion that the variegated color pattern and the monochromatic condition arising from it as sports are non-Mendelian in inheritance. Correns, however, has shown that in *Mirabilis jalapa* the inheritance of these sports is distinctly Mendelian, and the results of East and Hayes indicate the same for *Zea mays.* In this paper I shall present data from maize and attempt to show how they can be interpreted in strictly Mendelian terms.

Variegation is distinguished from other color patterns by its incorrigible irregularity. It is perhaps most often seen in the coloration of flowers and leaves but also occurs in fruits, seeds, stems, and even roots of various plants.

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[1] The experimental results reported here were presented at the Cleveland meeting of the American Society of Naturalists, January, 1913.

It is characteristic of the ears of certain varieties of maize known, at least in the Middle West, as ''calico'' corn. In these varieties the pericarp of most of the grains has few to many narrow stripes of dark red, the remaining area being colorless or showing a sort of washed-out red. Often broad red stripes appear on some grains, a single stripe covering from perhaps one tenth to nine tenths of the grain. Not uncommonly there are entirely colorless grains (so far as pericarp is concerned) and also solid red grains scattered over the ear. Much more rarely there is found a ''freak'' ear with a large patch of self-red or nearly self-red grains. Or sometimes an ear is composed largely of red or almost red grains with a small patch of striped or nearly colorless grains. In such cases it is not uncommon for the margin of the red area to cut across a grain so that one side—always the side toward the red patch—is red and the other side colorless or striped. Ears that are colorless throughout, except for a single striped grain, are not unknown and there are even known ears that are red except for a single striped grain. Very rarely a plant has one self-red ear and one variegated ear on the same stalk. It is also conceivable that all the ears of a plant might thus become red, but of course such a red-eared plant rising as a bud-sport could not ordinarily be distinguished from a red-eared plant arising as a seed-sport.

Variegated ears generally have variegated cobs, the amount of red in the cob ordinarily varying with the amount of red on the grains. In some ''freaks'' a part of the cob is solid red and the rest variegated. In a few such cases the red part of the cob corresponds exactly in position to the freak patch of grains. This is more frequently true when the grains of the freak patch are dark variegated than when they are self-red. In other ears there is no change in the cob corresponding to the change in the grains. The husks of variegated ears are also rather commonly variegated. In a few freak ears the red side of the ear is enclosed in reddish husks, the remainder of the husks being light striped. Red-eared plants arising as seed-sports always have solid red cobs and usually solid reddish husks.

The first account, so far as I am aware, of the inheritance of the striking somatic variations so commonly found in variegated plants was given by de Vries[2] in his discussion of ever-sporting varieties. The study was made in the years from 1892 to 1896 with a variety of *Antirrhinum* with striped flowers. De Vries's records are reproduced diagrammatically in Fig. 1.

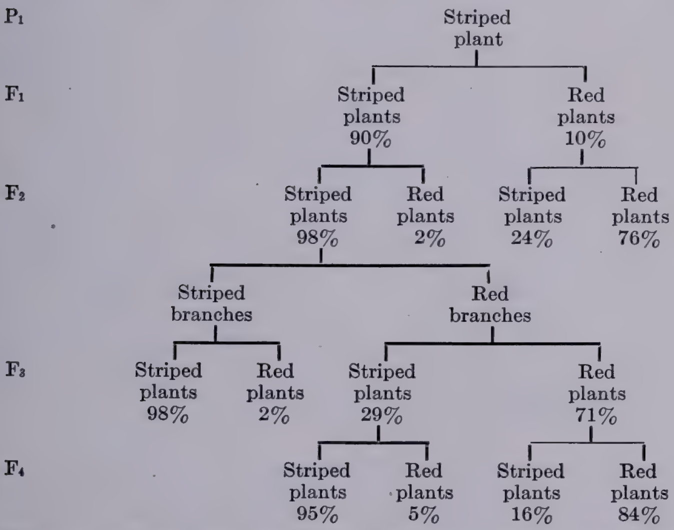

FIG. 1. DIAGRAM FROM DE VRIES'S RECORDS SHOWING THE INHERITANCE OF VARIEGATION AND SELF-RED IN THE FLOWERS OF *Antirrhinum*.

Of these results de Vries says:

> From these figures it is manifest that the red and striped types differ from one another not only in their visible attributes, but also in the degree of their heredity. The striped individuals repeat their peculiarity in 90–98 per cent. of their progeny, 2–10 per cent. sporting into the uni-

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[2] Vries, Hugo de, "Species and Varieties," pp. 309–328 (1905).

form red color. On the other hand, the red individuals are constant in 71–84 per cent. of their offspring, while 16–29 per cent. go over to the striped type. Or in one word: both types are inherited to a high degree, but the striped type is more strictly inherited than the red one.

De Vries's results were in some respects very similar to those of Correns and it is probable that he would have interpreted them in the same way had he then been familiar with Mendelian phenomena.

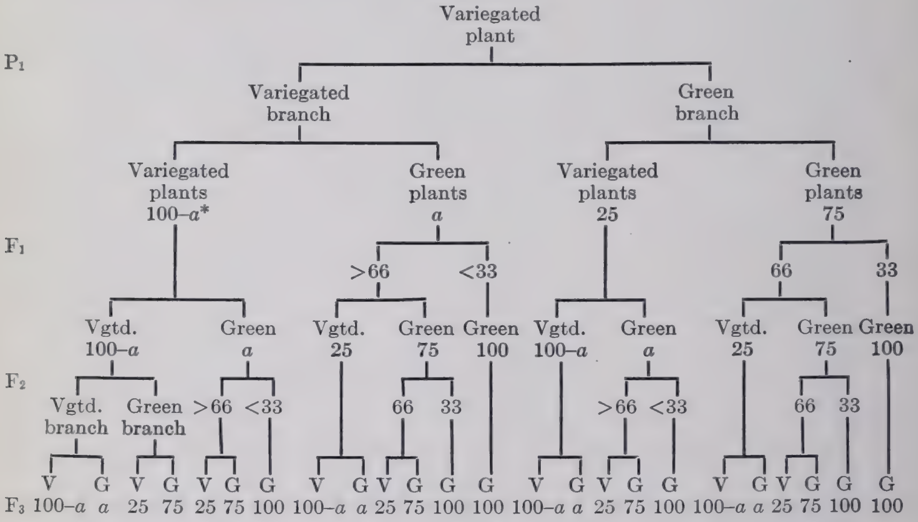

FIG. 2. CORRENS'S DIAGRAM SHOWING THE INHERITANCE OF VARIEGATION AND SELF-GREEN IN THE LEAVES OF *Mirabilis jalapa.*

Correns[3] has reported results of a careful study of the inheritance of the self-green condition appearing as a bud-sport on variegated-leaved plants of *Mirabilis jalapa,* and also of a self-color appearing in striped-flowered plants of the same species. His results for self-green and variegation of the leaves are shown diagrammatically in Fig. 2. The results are stated in approximate percentages. I have seen no report in which the detailed records were given.

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[3] Correns, C., *Ber. Deutsch. Bot. Gesel.,* 28: 418–434, 1910. *Der Ubergang aus dem homozygotischen in einen heterozygotischen Zustand im selben Individuum bei buntblättrigen und gestreiftblühenden Mirabilis-Sippen.*

* Numerals indicate approximate percentages; $a = 0$–10 per cent.

The diagram shows that a variegated branch of a variegated plant produces in F_1 mainly variegated plants, but occasionally a wholly green plant, while a green branch from the same plant produces in F_1 25 per cent. variegated and 75 per cent. green plants. The F_1 variegated plants, however produced, behave in later generations just like the original variegated parent plant. The F_1 green plants, whether produced from green or variegated branches, are always of two sorts, namely, those that are homozygous and therefore breed true green, and those that are heterozygous and therefore produce progenies of green and variegated individuals in a ratio of approximately 3 to 1. Correns points out that a green branch of a variegated plant behaves as though it belonged not to a variegated plant at all, but to a hybrid between a variegated plant and a green one, in which green is dominant, and that half of the germ cells produced by the green branch carry a factor for green and the other half a factor for variegation. Similar results were secured from branches with self-colored flowers on plants with striped flowers, except that such branches produce few if any more self-colored plants than are produced by branches with striped flowers. Plants with self-colored flowers, no matter how they arise, behave as they would if they had occurred in an F_2 progeny of a cross of striped by self-colored plants.

RESULTS OF EXPERIMENTS WITH MAIZE

Hartley[4] in 1902 gave an account of an experiment with variegated maize. In a comparatively pure white strain, which occasionally produced a red ear, there was found an ear similar to some of the "freak" ears noted earlier in this paper. It is described as being red except for a spot covering about one fifth of the surface, in which the grains were white with fine red streaks. The excellent plate accompanying the account, however, shows that most of the ''red'' grains had white streaks at the crown and that the cob was light-colored, not red. From the near-red grains of this ear there was produced a crop of 84 red ears and 86 pure white ones, while from the variegated grains of the same ear there came 39 light variegated ears and 36 white ones. Hartley refers to the parent ear as a ''sport or sudden variation from the type'' but does not indicate whether the ''type'' in mind was the white variety or the red ears occasionally produced by it. Both the color of the grains and cob and the production of about 50 per cent. of white ears from both the red and the variegated grains indicate very clearly that the parent ear was a heterozygous, variegated one and that it probably came from a white seed crossed by a stray grain of pollen from a variegated-eared plant, just as the occasional red ears in the white variety were certainly produced by stray pollen from red-eared plants.

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[4] Hartley, C. P., Yearbook, U. S. Dept. Agr., 1902: 543–544.

More recently East and Hayes[5] reported like behavior of a similarly variegated ear. An ear having on one side solid red grains and on the other white and very light variegated grains, similar to some of the ''freak'' ears noted earlier in this paper furnished the material for the test. The ear was produced from a white seed in a field of otherwise pure white corn and was therefore doubtless heterozygous for pericarp color and was probably pollinated in large part from plants without pericarp color, so that 50 per cent. white-eared plants were to be expected in its progeny. The white, the light variegated and the solid red grains were planted separately. The white and the variegated seeds alike produced light variegated and white ears, 15 of the former and 15 of the latter. The red seeds produced 22 white ears and 22 solid red ears. The authors' interpretation of these results is that the white seed which gave rise to the original colored ear had been fertilized by pollen from a red-eared plant and that the F_1 plant, "due to produce a red ear varied, somatically so that one half of the ear was red and one half striped." The authors further state:

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[5] East, E. M., and Hayes, H. K., Bul. Conn. Agr. Expt. Sta., 167: 106–107. 1911.

> This variation was transmitted by seeds, but at the same time the hybrid character of its seeds was unchanged as shown by their segregation into reds and whites in the next generation and the normal segregation of the hybrid dark reds in a further generation.

In the light of my own observations, it is equally possible and seems more likely that the white seed from which the original red-and-variegated ear came was the result of pollination from a plant with variegated ears, and that the somatic variation was from variegated grains to solid red grains rather than from red to variegated. But the important fact is that a somatic variation was later inherited in a strictly Mendelian way.

In 1909 I obtained results somewhat similar to those reported by East and Hayes. A few "freak" ears were secured, mainly from local and national corn expositions. Nothing was learned as to their parentage or pollination. Obviously, however, the parentage of the red, the variegated, and the white grains of any one ear was the same, and it is reasonable to suppose that the different sorts of grains of any one ear were pollinated with approximately the same kind or the same mixture of pollen. The results, as shown below, were essentially like those of Hartley and of East and Hayes.

Seeds Planted	Number of Plants with		
	Red Ears	Variegated Ears	White Ears
Self-red..................	43	0	33
Variegated and white.......	0	22	29

The results from four other ears were somewhat different, probably owing to differences in their pollination. (See Fig. 3.) They were as follows:

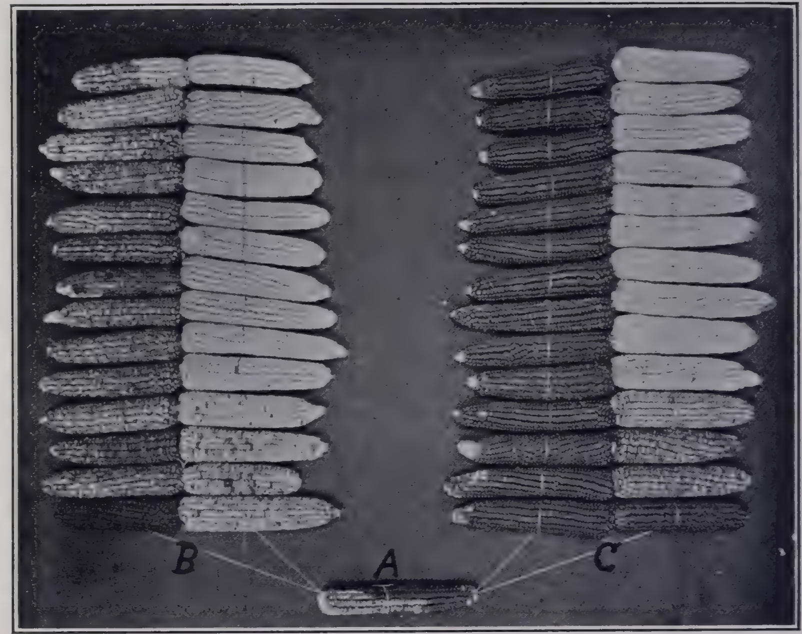

FIG. 3. *A*, "freak" ear of maize; *B*, progeny of striped seeds; *C*, progeny of self-red seeds.

Seeds Planted	Number of Plants with		
	Red Ears	Variegated Ears	White Ears
Self-red..................	128	32	69
Variegated and white.......	8	103	68

Two other ears of similar history, while they gave quite as striking results as those noted above, probably do not belong here since none of their immediate progeny were variegated and no variegated ears have occurred in later generations. These two ears were made up of red grains and white grains only. The results were as follows:

Seeds Planted	Number of Plants Red Ears	 White Ears
Red	77	85
White	0	122

The white ears bred true in later generations and the red ears produced reds and whites in typical Mendelian fashion. No such somatic variations as these have occurred in my cultures of self-red or white maize, so that I have been unable to study them further. Somatic variations in variegated corn, however, are not rare. Unfortunately several of the most pronounced of those occurring in my cultures were open-pollinated and therefore of little or no use in a careful study. I have therefore been obliged to make use in large part of the few solid red and nearly solid red grains scattered over otherwise more or less evenly variegated ears.

From twenty-three self-pollinated, variegated ears of plants that were homozygous for pericarp color, grains with various amounts of red were selected and planted. The results are summarized as follows:

Seeds Planted	Number of Plants with		
	Self-red Ears	Variegated Ears	Non-red Ears
Self-red	8	9	0
Nearly self-red	56	16	0
More than half red	9	34	0
Less than half red	5	22	0
Narrow red stripes	33	394	0
Non-red	1	22	0

Besides these 23 ears, 20 other selfed ears from homozygous plants contained only narrow-striped seeds from which there were produced 16 plants with red ears, 280 with variegated ears, and none with white ears. Similarly 21 selfed ears with narrow-striped seeds only, from plants that were heterozygous for pericarp color, produced 28 plants with red ears, 411 with variegated ears, and 208 with non-red[6] ears. Variously colored grains from 42 self-pollinated, heterozygous, variegated ears gave the following results:

Seeds Planted	Number of Plants with		
	Self-red Ears	Variegated Ears	Non-red[7] Ears
Self-red	15	1	6
Nearly self-red	17	8	8
More than one half red	46	51	31
Less than one half red	8	34	21
Narrow red stripes	57	767	300
Non-red	0	10	6

In the progenies of these 63 self-pollinated ears that were heterozygous for pericarp color, there were approximately 2.5 plants with pericarp color to one without it. All the classes of grains from self-red to non-red yielded both colored and non-colored ears, thus indicating, as already shown by East and Hayes, that the somatic variation in the seeds does not change their hybrid character. Considering only the plants with pericarp color, in the progenies of both heterozygous and homozygous variegated ears, 106 progenies in all, marked differences are seen in the percentages of self-red ears from seeds of the different color classes, as follows:

Seeds Planted	Number of Plants with		Per Cent. Self-red Among Colored Ears
	Self-red Ears	Variegated Ears	
Self-red	23	10	69.7
Nearly self-red	73	24	75.3
More than one half red	55	85	39.3
Less than one half red	13	56	18.8
Narrow red stripes	134	1,852	6.7
Non-red	1	32	3.0

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[6] Some of these ears had what I have termed "half-red" pericarp, *i. e.,* pericarp with a reddish color extending part way from the base to the crown of the seeds. (See Ann. Rpt. Nebr. Agr. Expt. Sta., 24: 62. 1911.) Half-red differs from self-red and variegated red not only in distribution but also in almost never developing fully in the heterozygous condition. It is hypostatic to self-red, but shows between the red stripes of variegated seeds. Since its presence does not mask either self-red or variegated-red and since it is strictly allelomorphic to both of them, half-red is here included with non-red. Variegated ears have never, in my observation, produced half-red grains as somatic variations.

[7] Some of these were half-red. (See footnote 6.)

In comparison with the cases reported by Hartley and by East and Hayes and one of my first cultures from open-pollinated ears, in all of which red grains produced no variegated ears and striped grains no red ones, the striking features of the results from these 106 self-pollinated ears are the facts that the wholly red grains yielded some variegated as well as red ears and that the striped grains and even the wholly non-red grains yielded some red as well as variegated ears. The percentages noted above indicate in a general way that for self-pollinated, variegated ears, *the more red there is in the seed planted the larger the percentage of red ears in the progeny.* These records, however, do not give a wholly trustworthy indication of the mode of inheritance of the somatic variations concerned here. If there is a modification of some factor in the female gametes, associated with a visible modification of somatic cells of the pericarp and even at times of the cob and husks, modifications that do not become visible until long after the gametes are formed, may there not be a similar modification of the same factor in the male gametes, though here not associated with any visible change in somatic cells because of the fact that the staminate inflorescence dies too soon after the pollen is shed? If male gametes do carry such modified factors and if the modification is as irregular in occurrence as the somatic modifications seen in variegated ears, so that any part of the tassel, from all to none, may produce gametes with the modified factor while not showing any visible somatic modification, it is obvious that the real nature of the male gametes of any variegated-eared maize plant can not be foretold. The mere fact that a variegated ear is self-pollinated, therefore, does not insure that its seeds are fertilized with pollen of known character.

That the male gametes of variegated-eared maize do often carry factors for self-red is shown by crosses of pure non-red strains with pollen from plants with variegated ears. The plants that furnished the pollen for these crosses were in some cases the same ones whose self-pollinated ears were concerned in the records discussed above. The results of these crosses are summarized here. Eight non-red ears crossed by plants that were homozygous for pericarp color yielded 17 red-eared, 116 variegated-eared and 8 white-eared[8] plants. Similarly, 14 ears of pure non-red strains crossed by pollen from plants heterozygous for pericarp color yielded 26 red-eared, 192 variegated-eared and 229 white-eared plants. Considering merely the plants with colored ears, 22 crossed ears produced 43 red-eared to 308 variegated-eared plants, or a little over 12 per cent. self-red.

Since the male gametes of variegated-eared corn have now been shown occasionally to carry a factor for self-red, it is obvious that only from crosses of variegated-eared plants with pollen from pure non-colored strains, can a definite idea of the inheritance of the somatic variations in pericarp color be gained.[9] Twelve ears from homozygous, variegated plants cross-pollinated by non-red strains might have afforded important evidence, but for the fact that 7 of them contained only narrow-striped grains and the other 5 no fully or even nearly self-red grains. The results are summarized here:

Seeds Planted	Number of Plants with		
	Self-red Ears	Variegated Ears	Non-red Ears.
More than one half red	5	11	0
Less than one half red	0	15	0
Narrow red stripes	2	281	0
Non-red	0	22	0

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[8] Some of the 8 white ears may have been extreme light types of variegation, for in some other cases very light variegated and wholly white ears have been observed on the same plant. And of course some of them may have been due to accidental pollination of the parent ear.

[9] Though the genetic factors for pigment patterns in maize seem to be distinct from the factors for the pigment concerned in these patterns, no non-colored maize that I have used has ever given any indication in crosses of carrying pattern factors.

The principal facts of interest here are the production of only one red-eared plant to about 140 variegated-eared ones from narrow-striped seeds, and of about one red-eared to two variegated-eared plants from seeds with from one half to perhaps three fourths red.

Of 20 variegated ears, heterozygous for pericarp color, that were crossed with pollen from pure non-colored strains, 5 had only narrow-striped grains and 15 had variously broad-striped grains and even some self-red ones. The summaries of these crosses are as follows:

Seeds Planted	Number of Plants with		
	Self-red Ears	Variegated Ears	Non-red Ears
Self-red	9	0	11
Nearly self-red	5	0	2
More than one half red	4	2	2
Less than one half red	3	5	9
Narrow red stripes	7	265	301
Non-red	0	27	20

Here again, just as with homozygous, variegated ears, *the more red there is in the pericarp the more likely are the female gametes to carry a factor for self-red.* While the number of individuals dealt with are too few to afford reliable evidence, it is suggestive to note that the ratio of red-eared to variegated-eared plants, though not the ratio of red-eared to total plants, is greater in case of parent ears that are heterozygous than of those that are homozygous for variegated pericarp.

So far nothing has been said of the results in generations later than the one grown from the selected seeds (F_1). Let us now see what results follow when the variegated ears and the red ears produced as explained above become the parents of second generations (F_2) from the selected seeds. The variegated ears so produced behave like the original variegated ears from which seeds were selected and their progenies have, therefore, been included in the data already presented. There remains only to present the records of the progenies of red ears.

Data are available from 7 F_1 red ears obtained from self-pollinated, homozygous, variegated plants. Five of these red ears were self-pollinated and two were crossed with pure white-eared plants. The results in F_2 and F_3 were as follows:

Seeds Planted from	Number of Plants with		
	Self-red Ears	Variegated Ears	Non-red Ears
F_1 reds from selfed, homo., vgtd. P_1's			
5 ears selfed	119	37	0
2 ears × white	46	45	0
F_2 reds from selfed F_1 reds			
1 ear selfed	9	2	0
1 ear selfed	16	0	0
F_2 reds from F_1 reds × white			
1 ear selfed	26	0	5
2 ears × white	40	0	37

The above is approximately what would have been expected, had *the F_1 red ears that arose from self-pollinated, homozygous, variegated-eared plants been produced by a cross between red-eared and variegated-eared races.*

Of the F_1 reds arising from self-pollinated, heterozygous, variegated-eared plants, nine were selfed and two were crossed with whites. The results secured in F_2 and F_3 follow:

Seeds Planted from	Self-red Ears	Variegated Ears	Non-red Ears
F_1 reds from selfed, hetero., vgtd. P_1's			
3 ears selfed (a)	104	23	0
1 ear × white	6	7	0
6 ears selfed	105	0	38
1 ear × white	12	0	7
F_2 reds from selfed F_1 reds of (a)			
4 ears selfed	59	12	0
1 ear selfed	23	0	0

From the above it appears that *the F_1 red ears, arising from self-pollinated, heterozygous, variegated-eared plants behave in some cases as if they were hybrids between red-eared and variegated-eared races and in other* *cases as if they were hybrids between red-eared and white-eared races.*

Of the four possible sorts of red-eared "sports" from variegated-eared plants, two remain to be treated. Because of their similar behavior they will be considered together here. Of the F_1 red ears arising from homozygous, variegated-eared plants that had been crossed with white-eared races, three were self-pollinated and two crossed with whites. Of the F_1 red ears arising from heterozygous, variegated-eared plants that had been crossed with white-eared races, four were selfed. The results in F_2 and F_3 are:

Seeds Planted from	Self-red Ears	Variegated Ears	Non-red Ears
F_1 reds from vgtd. P_1's × white			
P_1's homozygous			
3 ears selfed	54	0	16
2 ears × whites	34	0	43
P_1's heterozygous			
4 ears selfed	102	0	47
F_2 reds from selfed F_1 reds			
3 ears selfed	32	0	10
1 ear selfed	43	0	0

So far as these results go they indicate that *F_1 reds arising from crosses between both homozygous and heterozygous, variegated-eared plants and white-eared races behave as if they were hybrids between red-eared and white-eared races.*

One homozygous, variegated-eared plant was cross-pollinated by a homozygous red race. From the variegated ear produced, self-red, nearly self-red, and narrow-striped seeds were planted. All resulted, of course, in red-eared F_1 plants, 16 in all. A self-pollinated F_1 red ear from a narrow-striped seed gave in F_2 24 red-eared and 11 variegated-eared plants—somewhat fewer reds than were to have been expected. An F_1 red ear from a nearly self-red grain, when cross-pollinated with non-red, yielded 9 reds and 11 variegated in F_2. A third F_1 red-eared plant, this one from a self-red grain of the variegated parent ear, bred true red in F_2. One ear of this F_1 plant was selfed and yielded 14 reds in F_2, and another ear was cross-pollinated by non-red and yielded 29 reds.

There are various other somatic variations rather frequently seen in maize, but they are apparently not inherited. There are sometimes found variegated ears with a large patch of self-red cob but with little or no corresponding change in the color of the overlying grains. I have as yet no evidence that this somatic variation in cob color is inherited through the seeds of the self-red part of the cob. Such seeds apparently always produce ears with variegated grains and variegated cobs, just as do other seeds of the same parent ear. Of course variegated seeds from a self-red patch of cob occasionally give rise to a self-red ear, as discussed in detail in this paper, and such red ears always have self-red cobs, but this is also true of all self-red ears, whether or not they are produced by red or by variegated seeds and without respect to whether the part of the cob underlying these seeds is self-red, finely variegated, or entirely white.

Another form of somatic variation seen in ears of maize is the occurrence of patches of considerable size, the grains of which, though variegated, are much darker in color than the grains of the rest of the ear. Such patches of grains are often quite as strikingly distinct in appearance as patches of self-red grains, and are apparently even more likely to correspond exactly in outline with an underlying patch of self-red cob than are patches of self-red grains. Moreover, such dark, variegated grains often present a rather definite color pattern. The crowns are often made to appear almost solid red by the widening and convergence at the crown of narrow red stripes extending down toward the base of the grain particularly on the side opposite the germ. Another type of dark, variegated grains differs from the lighter, variegated grains of the same ear principally in the greater development of the somewhat washed-out red apparently underlying the dark red stripes of the variegation pattern proper. I have grown numerous progenies from dark and light variegated grains of the same ears, but as yet have no evidence that such somatic variations are inherited. Notwithstanding this, I have strains of maize breeding true to a very dark type of variegation, others to a medium sort of variegation, and still others to exceedingly light types of variegation. There can be no doubt that some of these different types of variegation are inherited, but the mode of inheritance in crosses has not been fully worked out.

One other form of grain coloration that might be called an extremely dark type of variegation is to be noted. The grains are self-red throughout except for a nearly colorless crown formed by converging light stripes extending some way down the side of the grain opposite the germ, almost exactly the reverse of one of the types of dark variegation described above. Variegations of this sort behave in inheritance almost exactly like fully self-red grains, giving a large percentage of red-eared progeny. And these red ears are apparently always fully self-red, never showing the pattern of converging light lines seen in the parent seeds. Many such seeds have been included in the results recorded earlier in this paper where they were listed as "nearly self-red."

Interpretation of Results

Any interpretation of the data presented here must take account of these facts: (1) that the more red there is in the pericarp the more frequently do red ears occur in the progeny, and (2) that such red ears behave just as if they were F_1 hybrids between red and variegated or red and white races. The development of red in the pericarp is evidently associated with and perhaps due to a modification of some Mendelian factor for pericarp color in the somatic cells. The zygotic formula of a plant homozygous for variegated pericarp may be designated as *VV*, and that of a plant heterozygous for variegated pericarp as *V*—. If in any somatic cell *VV*, from unknown causes, a *V* factor were transformed into a factor for self-color, *S*, that cell would then have the formula *VS*. Any pericarp cells descended from it would without further modification be red. If all the pericarp cells of a seed were thus descended, the seed would be self-red, just as it would if the plant bearing it were a hybrid between pure red and variegated races. Moreover, one half of the gametes arising from such somatic cells would carry *V* and one half would carry *S*, just as if the plant were a hybrid of red and variegated types. Or, if both *V* factors were changed, the grains would be self-red as before, but all instead of half the gametes would carry *S*. If, however, the modification from *VV* to *VS* should occur very early in the life of the plant, or even of the embryo, all the ears of the plant might thereby become self-red, and one half of all the gametes both male and female might then carry *S* and the other half *V* as in the ordinary hybrid. Or the plant might then become a sectorial chimera with one variegated ear and one red ear, the gametes from the one side of the plant all carrying *V*. If the modification occur much later, say soon after the ear begins to form, there might then be merely a solid patch of red grains on an otherwise variegated ear. In this case only those gametes arising from these smaller masses of tissue would carry half *S* and half *V*. If, however, the modification occur after the grains begin to form, the latter might be perhaps three fourths red, or one half red, or merely have narrow stripes of red, depending upon the amount of pericarp directly descended from the modified cell. In this case it seems reasonable to assume that the larger the mass of modified tissue the greater the chance that the gametes concerned should carry *S*. Finally, if in certain grains the change never occurs, they should show no red and the gametes formed in connection with them should all carry *V*, none *S*.

Similarly, it may be assumed that in any cell of a heterozygous, variegated-eared plant, *V*—, the *V* factor may as before become an *S* factor. The effect on pericarp color would be exactly the same as in a homozygous, variegated plant, and, of the gametes arising from the modified tissue, one half would carry *S* as in the other case, but the other half, instead of carrying *V*, would carry no factor and would be represented by —.

If the interpretation suggested here is correct, it is to be expected that the more red there is in the pericarp of any seeds, *i. e.*, the larger the mass of tissue descended from the cell in which the change from *V* to *S* took place, the greater the chance that the female gametes concerned carried the factor *S*. With heterozygous, variegated-eared plants, *V*—, however, never more than half of the gametes concerned could carry *S* even in case of self-red grains, the other half of the gametes carrying no factor, —. Of the heterozygous, variegated ears the progenies of which have been reported here, some were selfed, some crossed with white, and some open-pollinated. From self-pollinated ears, self-red and nearly self-red seeds yielded 32 red-eared, 9 variegated-eared, and 14 non-red-eared plants, or practically 58 per cent. self-red. This excess of self-red ears may be due, in part at least, to the presence of the *S* factor in some of the male gametes concerned, but the numbers are too small to give very reliable indications. From similar ears that instead of being selfed were crossed with white, so that the results could not have been influenced by factors present in the male gametes, self-red and nearly self-red seeds produced 14 plants with red ears and 13 with non-red ears, or about 52 per cent. red. While these numbers are very small, the fact that no variegated ears were produced, but that every ear with any red color was self-red, is noteworthy. From the open-pollinated, heterozygous ears included in my cultures self-red seeds gave progenies consisting of 171 red-eared, 32 variegated-eared, and 102 non-red-eared plants, or about 56 per cent. red.

In case of homozygous, variegated-eared plants, *VV*, all the gametes associated with seeds that later become self-red could carry *S* only if both *V* factors of the somatic cells from which the gametes arise were changed to *S* factors. Because of the rarity of changes from *V* to *S*, unless both *V* factors are influenced alike by whatever causes the change, so that both change simultaneously to *S* factors, the chance is slight that more than one will ever change. In the latter case only about 50 per cent. of the gametes associated with self-red grains of homozygous, variegated ears could be expected to carry *S*, just as in the case of heterozygous ears. None of the open-pollinated ears whose progenies I have grown were homozygous for variegated pericarp, and none of the homozygous ears that had been crossed with white contained any self red or nearly self-red seeds. The only data, therefore, that bear upon the point at issue are those obtained from self-pollinated, homozygous, variegated ears. The self-red and nearly self-red seeds of such ears produced 64 red-eared and only 25 variegated-eared plants, or about 72 per cent. self-red. This may mean that in some cases both *V* factors were changed to *S* factors, but the results may just as likely be due to the presence of *S* in an unusually large percentage of the male gametes concerned. The production of the 25 variegated-eared plants, however, is very good evidence that, in at least a very considerable number of cases, not more than one of the two *V* factors could have been changed to *S*.

If the change from *V* to *S* should happen to occur at such a time that the grain rudiments became sectorial chimeras consisting of say one half modified cells and one half unmodified ones, one half of the pericarp would be expected to show red color and the other half no color. It would be expected further that the chances of a particular gamete's arising from a modified or from an unmodified cell would be equal. If then one half of the gametes associated with these one-half-red grains arise from cells in which only one of the V factors has been changed to S, one fourth of the gametes should carry S and three fourths should carry V, or one fourth S, one fourth V, and one half —, depending upon whether the ears concerned are homozygous or heterozygous for variegated pericarp. Such grains from homozygous ears should, therefore, whether selfed or crossed by white, yield about one red ear to three variegated ones. Similarly, from heterozygous ears, grains with one half their pericarp red should yield about one red to two variegated to one white if self-pollinated and one red to one variegated to two white if crossed by white. (This is on the assumption that no S factors are carried by the male gametes.) Let us assume that by lumping together all the seeds listed in the foregoing records as "more than one half red" and as "less than one half red" the whole lot would average about one half red, and compare the results with the expectation as noted above. From grains of these two classes from homozygous ears both selfed and crossed by white, there resulted 19 red-eared and 82 variegated-eared plants, or a ratio of about 1:4.3 instead of 1:3. From heterozygous ears self-pollinated grains of these two classes yielded 54 red-eared, 85 variegated-eared, and 52 white-eared plants, and similar grains crossed by white yielded 7 red-eared, 7 variegated-eared, and 20 white-eared plants, or ratios of 1.04:1.63:1 and 1:1:2.86 instead of 1:2:1 and 1:1:2, respectively. The observed ratios are certainly suggestive but must not be given undue importance, for there is no assurance that the seeds used really averaged one half red and no assurance that some of the male gametes in the case of the selfed seeds did not carry *S*.

We must now examine the results secured in generations later than F_1, and note whether the hypothesis under consideration applies equally well to them.

It will be recalled that F_1 red-eared plants that arose from homozygous, variegated ears which had been self-pollinated (see page 18) yielded in F_2 only red-eared and variegated-eared progeny. On our assumption the formula of the parent variegated ears was *VV*, but the red grains of these ears were *VS* and the gametes associated with them therefore either *V* or *S* or all *S*. Female gametes carrying *S* would have produced red ears in F_1 whether the male gametes carried *S* or *V*, and female gametes with *V* could not have produced red ears except when the male gametes uniting with them carried *S*. The F_1 red-eared plants must therefore have been *VS* or *SS*, the former being expected much more frequently than the latter, owing to the rarity of *S* in male gametes. Only 7 such red ears were tested and all yielded red and variegated ears in typical Mendelian ratios, showing that all of them were *VS* like any F_1 hybrid between red and variegated races. Of two F_2 reds from selfed F_1's, one again yielded reds and variegates and one apparently bred true red. Three F_2 reds, from F_1 reds crossed by whites, yielded reds and whites only—typical Mendelian results throughout.

When F_1 red-eared plants arose from either homozygous or heterozygous, variegated ears that had been cross-pollinated by whites they yielded only red-eared and white-eared, never variegated-eared, offspring (see page 19), just as if they were F_1 ears of a cross of reds with whites. By hypothesis the parent variegated-eared plants were *V*— and *VV*, and their red grains *S*— and *SV* (or possibly *SS*). The gametes associated with such grains were therefore *S* and —, and *S* and *V* (or possibly all *S*).

The male gametes from white races were all —. The F_1 plants were therefore S—, V—, and ——, only those with S— having red ears. The five red-eared F_1 plants that were tested produced in F_2 red-eared and white-eared plants in Mendelian ratios. Of the F_2 red-eared plants one bred true in F_3 and three again segregated into reds and whites.

When heterozygous, variegated, parent ears were self-pollinated, the F_1 red-eared plants behaved in some cases like hybrids of red with variegated races and in other cases like hybrids of red with white races (see page 18). Our assumption is that the variegated-eared parent plants were V— and their red grains S—. The gametes associated with these red grains were of course S and —. The male gametes of the same plants were doubtless largely V and —, though a few were probably S. The F_1 plants must therefore have been ——, V—, S—, SV or SS. Reds with SS would be expected only rarely, and of the 11 F_1 reds tested none had that formula, else they would have bred true in F_2. Seven of the 11 F_1 reds evidently were S—, for they yielded F_2 progenies consisting of reds and whites only. Four of the 11 were obviously SV, for they yielded F_2's of reds and variegates only. Of the latter F_2 reds, one bred true in F_3 and four again segregated into reds and variegates.

From a self-red seed of a homozygous, variegated ear that had been cross-pollinated by a pure red race, an F_1 red-eared plant was produced and this plant bred true red in F_2. From a nearly self-red seed of the same variegated, parent ear, an F_1 red was produced but yielded reds and variegates in F_2 just as did a similar F_1 ear from a seed with narrow red stripes (see page 19). The variegated parent ear was VV and the red and near-red grains probably VS. The gametes associated with these grains were V and S. The male gametes were all S. Therefore the F_2 reds were in part VS and in part SS.

By way of summary, it is recalled that, in all, 28 F_1 red-eared plants were tested by F_2 progenies. Only one of these bred true and that one came from a red grain of an ear that had been cross-pollinated by a pure red race. Disregarding the three F_2 red-eared plants thus produced and the 9 red ears produced from seeds of variegated ears that had been cross-pollinated by white races and that therefore could not have bred true, there remain 16 F_1 reds, none of which bred true in F_2. Had these F_1 red-eared plants behaved as did the F_1 green-leaved plants produced by green branches of variegated-leaved parents in Correns's experiments, approximately 5 of the 16 should have bred true. It will be recalled that Correns found that such green branches always produced green-leaved and variegated-leaved plants in the ratio of 3:1, and that one of the three bred true and the other two again segregated, just as must have happened if the green branch had been a part of an F_1 hybrid of green with variegated instead of a part of a homozygous variegated plant.

The difference between *Zea* and *Mirabilis* is, however, not a fundamental one, but is due merely to the circumstance that *Mirabilis* has perfect flowers while *Zea* is monecious. In *Mirabilis* both male and female gametes of a green branch arise from somatic cells in which the V factor has changed to a G factor. If a change in only one V factor is responsible for the production of the green branch, the somatic cells of such a branch must all be VG and the results reported by Correns are the only ones to be expected. With *Zea mays,* however, all the grains of one ear of a variegated-eared plant might arise from cells having VS, so that half of the female gametes would carry S, while little or no corresponding change might take place in the staminate inflorescence and therefore no (or very few) male gametes would carry S. From such an ear of maize only about one half, instead of three fourths, of the F_1 plants should have red ears and none (or very few), instead of one third, of the F_1 plants should breed true.

The occasional green plants ("*a*" per cent.) arising from variegated branches in Correns's experiments with *Mirabilis* are more nearly comparable to F_1 red-eared maize plants than are the green plants arising from green branches. It is quite conceivable that on a variegated branch the male gametes might arise from cells that are *VG,* while the female gametes arise from cells that are *VV,* or the reverse, though this difference between male and female gametes would hardly be so common an occurrence as with maize where the staminate and pistillate inflorescences are situated so far apart. It is worthy of note in this connection that of the occasional green plants produced by selfed seed of variegated plants in Correns's experiments with *Mirabilis* (see diagram, Fig. 2), less than one third bred true and more than two thirds segregated into green and variegated. (Correns indicates this merely by the signs $<$ and $>$ in connection with 33 per cent. and 66 per cent. respectively, in his diagram, and gives no indication of how much less than 33 per cent. bred true or how much more than 66 per cent. segregated.)

De Vries's results with *Antirrhinum* yield readily to the same analysis used with *Zea* and *Mirabilis.* Selfed seed from striped-flowered branches gave a small per cent.—from 2 to 10—of red-flowered plants. Only a few of the red-flowered plants were tested and these were found to yield 76 per cent. red to 24 per cent. striped. Selfed seed from red-flowered branches of striped-flowered plants yielded 71 per cent. red-flowered and 29 per cent. striped-flowered plants, approximating the 75 per cent. and 25 per cent. indicated by Correns's results with *Mirabilis.* None of these red-flowered plants bred true, but only one test, and that of only a few plants, was made. The results were 84 per cent. red-flowered and 16 per cent.

striped-flowered plants. It seems quite likely that had de Vries tested more red-flowered plants he would have found some of them to breed true.

Correns's results with striped and red flowers of *Mirabilis* differed in one important respect from his results with variegated and green plants of the same species, as well as from the principal results with *Zea* reported here and from de Vries's results with striped-flowered and red-flowered forms of *Antirrhinum*. When red-flowered plants arose from striped-flowered varieties of *Mirabilis*, they behaved just as did the green plants that arose from variegated forms. But selfed seeds from wholly red-flowered branches of otherwise striped-flowered plants yielded little if any larger percentages of red-flowered plants than did selfed seeds from striped-flowered branches of the same plants. It would seem that in case of *Mirabilis* flowers, when the self pattern arises as a somatic variation from the variegated pattern there is no corresponding change in the Mendelian factors for these patterns. In case of seed-sports from variegated-flowered to red-flowered plants, however, the factors for variegation are affected just as in case of green plants arising from variegated ones and of red-eared maize plants arising from variegated-eared ones. The apparently non-inherited somatic variations of maize plants, noted briefly earlier in this paper, are possibly of the same nature as the somatic variations in variegated flowers of *Mirabilis*. Some of these variations in maize are self-red cob patches on otherwise variegated cobs, and dark, variegated grains occurring in patches or scattered over light, variegated ears.

GENERAL CONSIDERATIONS

The experiments of de Vries, Correns, Hartley, and East and Hayes, as well as the records reported in this paper, all indicate that certain somatic variations are inherited in strictly Mendelian fashion. All these somatic variations consist in the appearance of self-colors on plants that are normally variegated in pattern. The fact that variegated plants occasionally throw both bud-sports and seed-sports with self-colors is not, in general, to be taken as an indication that the variegated plants in question are heterozygous. Such behavior seems to be inseparably associated with variegation. Correns has pointed out (*loc. cit.*) that variegated *Mirabilis* plants can not be considered mosaics of green and ''chlorina'' types due to heterozygosis, since they do not segregate into chlorina and green, but into variegated and green. The same reasoning applies to variegation in the color of maize ears. Variegated-eared plants do not throw reds and whites, but reds and variegates. The conclusion seems irresistible that self-color occurring as a somatic variation is due to the change of a Mendelian factor for variegation into a factor for self-color. If this be granted, the behavior of these variations in later generations is a mere matter of simple Mendelian inheritance.

From the title of his paper and the tone of his discussion, it is clear that Correns regards, as the most significant feature of these inherited somatic variations, the change from a homozygous to a heterozygous condition. He even refers to them as cases of ''vegetativen Bastardierung'' or ''autohybridization.'' To me, however, the essential feature is the change of one Mendelian factor into another. The fact that this modification of genetic factors results in a change from homozygosis to heterozygosis seems wholly incidental. It follows from the circumstance that usually only one of the two *V* factors of somatic cells is modified. My own data do not in fact show that the change always affects only one of the factors at a time. While the results prove that this is true in a part of the cases at least, the F_1 ratios suggest the possibility of both factors being modified in some cases.

It is of course utterly impossible at the present time to conceive of the cause or even of the nature of this change in factors from *V* to *S*. We can only conjecture at present as to whether the change may possibly be associated with changing metabolic processes in the maturing plant, or perhaps be connected in some way with changing external influences, or even be a quality inherent in the *V* factor itself. It is perhaps significant that in maize, at least, the change, whatever its cause, occurs very rarely early in the life of the plant and apparently becomes increasingly more frequent as the plant matures. Wholly red ears in variegated-eared plants are extremely rare; large patches of red grains are somewhat less rare; individual red grains occur on most variegated ears; red stripes on the individual grains are very frequent, in fact all but universal in some strains, though in other strains —very light variegated ones—there may be only a few striped grains on a whole ear, the others being wholly colorless. As a matter of fact, even the presence of an ear with red pericarp throughout on a variegated-eared plant may not be good evidence that the change in factors occurred before the ear began to form. If the change took place before the ear was laid down, it would seem that the cob should always be self-red, since the red-eared progeny of such modified grains of the variegated parent plant invariably have red cobs, and cob and pericarp colors are coupled absolutely in later generations. But red ears, or nearly red ears, with light variegated instead of red cobs, have been found to occur as somatic variations on variegated-eared plants. Such behavior suggests that sometimes the factor change may occur almost simultaneously in the rudiments of every grain so that the grains become self-red while the cob remains variegated. We might, of course, account for the appearance of self-colored grains on a variegated cob on the basis of separate factors for cob and pericarp color[10] by the assumption that one of these factors may be modified while the other remains unchanged. But we should then have the no less difficult problem of accounting for the universal appearance of red cobs with F_1 red ears without respect to whether the parent grains stood on red or variegated cobs.[11]

Forced to its logical limit, our conception of the *V* factor is that of a sort of temporary inhibitor, an inhibitor that sooner or later loses its power to inhibit color development, a power that once lost is ordinarily never regained. Of course it may be that there is present in variegated maize merely a dominant factor for self-color, *S,* that is temporarily inactive, but that sooner or later becomes permanently active. Even if this be true, *S* as an active factor and *S* as an inactive factor are certainly as distinct in inheritance as they are in development and therefore deserve to be designated separately. And since in one case there results self-color and in the other variegation, the factors may as well be called *S* and *V* as anything else. It is of course also conceivable that the *S* factor may repeatedly arise *de novo,* though this seems very unlikely.

Whatever our conception of the nature of the factors for variegation and for self-color in maize ears, these factors are certainly as distinct in inheritance as any two factors could well be. Moreover, there is abundant evidence, which can not be given here, that they are strictly allelomorphic, as indeed they must necessarily be if one arises by modification of the other—this on the assumption that the factors are definitely localized in certain chromosomes. Furthermore, these factors are to be regarded as *pattern* factors. Though they must influence

[10] Evidence that there are distinct factors for cob and pericarp color was presented in a previous paper on coupling and allelomorphism in maize. Ann. Rpt. Nebr. Agr. Expt. Sta., 24: 59–90. 1911.

[11] This problem is discussed in another paper on the simultaneous modification of distinct Mendelian factors. Amer. Nat., 47: 633–636. 1913.

the development of the pigment in order to produce a pattern at all, they are now known to be distinct in inheritance from the factors for pigment—a fact that I have been able to show by use of a race of maize with a peculiar brown pericarp in addition to races with red pericarp.

SUMMARY

A somatic variation in maize is shown to be inherited in simple Mendelian fashion. The variation has to do with the development of a dark red pigment (or in one stock a brown pigment) in the pericarp of the grains, often associated with the development of an apparently similar pigment in the cob and husks.

Plants in which this pigment has a variegated pattern may show any amount of red pericarp, including wholly self-red ears, large or small patches of self-red grains, scattered self-red grains, grains with a single stripe of red covering from perhaps nine tenths to one tenth of the surface, grains with several prominent stripes and those with a single minute streak, ears with most of the grains prominently striped and ears that are non-colored except for a single partly colored grain, and probably also plants with wholly self-red and others with wholly colorless ears.

It is shown that the amount of pigment developed in the pericarp of variegated seeds bears a definite relation to the development of color in the progeny of such seeds. This relation is not such that seeds showing say nine tenths, one half, or one tenth red will produce or even tend to produce plants whose ears as a whole or whose individual grains are, respectively, nine tenths, one half, or one tenth red. Experimental results indicate rather that the more color in the pericarp of the seeds planted the more likely are they to produce plants with wholly self-red ears, and, correspondingly, the less likely to yield plants with variegated ears.

Self-red ears thus produced are shown to behave in inheritance just as if they were hybrids between self-red and variegated races or between self-red and non-red races, the behavior in any given case depending upon whether the parent variegated ears were homozygous or heterozygous for variegated pericarp and whether they were self-pollinated or crossed with white.

It is suggested that these results may be interpreted by the assumption that a genetic factor for variegation, V, is changed to a self-color factor, S, in a somatic cell. All pericarp cells directly descended from this modified cell will, it is assumed, develop color, and of the gametes arising from such modified cells one half will carry the S factor and one half the V factor if only one of the two V factors of the somatic cells is changed, or all such gametes will carry S if both V factors are changed.

The V factor is thought of as a sort of temporary, recessive inhibitor that sooner or later permanently loses its power to inhibit color development, becoming thereby an S factor. Or it may be that the dominant factor, S, is temporarily inactive, but sooner or later becomes permanently active. Again, the S factor may repeatedly arise *de novo*. The cause of any such change in factors is beyond intelligent discussion at present.

The results of Correns with *Mirabilis* and of de Vries with *Antirrhinum* are shown to be subject to the same analysis as that used to interpret the results secured with maize.

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REPORT OF EXPERIMENTAL SUBSTATION, NORTH PLATTE, NEBRASKA.

BY W. W. BURR.

W. P. SNYDER, Superintendent.

DISTRIBUTED JULY 1, 1914.

Apparatus and Method of Obtaining Soil Samples.

LINCOLN, NEBRASKA
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CONTENTS.

PAGE

- INTRODUCTION 5
- SUMMARY 8
- THE STORAGE AND USE OF SOIL MOISTURE 11
- General conditions 11
- Type of soil 11
  - Table 1.—Mechanical composition of upland soil at North Platte, Nebr. 12
- Depth of sampling 13
- Water in the soil 13
- Hygroscopic water 14
- Capillary water 14
- Gravitational water 15
- Maximum water-holding capacity of a soil 15
- Minimum point of exhaustion by the plant 16
  - Table 2.—Showing maximum water-holding capacity of this type of soil, 1908-1909. Hard table-land. Buffalo grass sod, 17
  - Table 3.—Minimum point of exhaustion of soil water by the crop, 18
- Storing water in the soil by summer tillage 19
  - Table 4.—Storing moisture by summer tilling. Per cent of moisture in the soil 19
  - Chart I.—Available water (above 8 per cent) stored by summer tillage 23
  - Chart II.—Per cent of moisture in first six feet of soil, 1908 24
  - Chart III.—Storing water by summer tillage 26
  - Chart IV.—Storing water by summer tillage 27
- Depth to which water has been stored in one season 29
  - Table 5.—Depth to which water has been stored in one year. Per cent moisture in the soil 30
- Effect of condition of soil at surface and character of rain on water retention 31
  - Table 6.—Effect of surface condition in retaining rainfall 33
  - Table 7.—Effect of surface condition and moisture content on storing water 33
  - Table 8.—Effect of amount of water in soil on penetration, 1909 34
  - Table 9.—Effect of surface and moisture content on storing water, 1910 34
  - Table 10.—Effect of surface and moisture content on storing water, 1912 35
  - Table 11.—Effect of surface and amount of water in soil, on penetration, 1912 37
  - Chart V.—Per cent of moisture in first six feet of soil, 1908 38
- Effect of cultivation 39
  - Table 12.—Effect of disking after the binder on soil moisture 40
  - Table 13.—Effect of disking aftr the binder 41
  - Table 14.—Effect of cultivation and weeds, 1912 43
  - Table 15.—Plowing versus disking, effect on soil moisture, 1907 43
  - Table 16.—Effect of cultivation on soil moisture, 1910 44
  - Table 17.—Effect of cultivation and growing weeds on soil moisture, 1908 45

PAGE
Artificial mulches 46
    Table 18.—Effect of mulching on soil moisture, 1912.............. 47
    Table 19.—Effect of mulching on soil moisture, 1911............. 48
Loss of water from the soil 49
Depths to which crops have used moisture 50
    Table 20.—Depths to which crops have used moisture. Summer tilled land 52
    Table 21.—Depths to which crops have used moisture. Summer tilled land 53
Effect of weeds 55
    Tables 22-27.—Effect of weeds on soil moisture, 1907-1913........56-60
    Chart VI.—Effect of cultivation and weeds, 1908.............. 61
    Chart VII.—Use of available water by a corn crop.............. 62
    Table 28.—Use of water from soil by spring wheat, 1913........ 64
    Chart VIII.—Showing available moisture (above 8 per cent) and its use by the crop 65
    Chart IX.—Showing available water (above 8 per cent) and its use by the crop 66
    Charts X, XI, XII, XIV, and XV.—Moisture content of plats continuously cropped to spring wheat 68-74
    Chart XI.—Moisture content of plat continuously cropped to spring wheat (1908) 69
    Table 29.—Effect of capillarity on soil moisture. Alfalfa on bench land 75
    Table 30.—Effect of capillarity on soil moisture................ 77
    Table 31.—Water required to produce one pound of dry matter of various crops 78
Water required to produce one pound of dry matter of various crops.. 78
Climatic conditions 80
    Fig. 1.—Normal annual precipitation in Nebraska. Map showing rain belts 81
    Fig. 2.—Precipitation at North Platte, Nebr., by years, 1875-1913, 82
    Table 32.—Record of precipitation by months for thirty-nine years, at North Platte, Nebr., as reported by the United States Weather Bureau 83
    Table 33.—Daily precipitation from March 1 to June 30, 1908-1913, 84
    Table 34.—Daily precipitation from July 1 to October 31, 1908-1913, 85
    Table 35.—Daily mean temperature from April 1 to August 31, 1908-1913 86
    Table 36.—Daily evaporation from April 1 to September 30. for the years 1908 to 1913 87
    Table 37.—Daily wind velocity per hour from April 1 to August 31, 1908-1913 88

THE STORAGE AND USE OF SOIL MOISTURE.

BY W. W. BURR.*

INTRODUCTION.

The profitable cultivation of the non-irrigable lands in west central and western Nebraska is limited by the amount and efficient use of the precipitation. There are tracts of land in the sand hills and minor tracts of badly worn heavier soils where the need of soil fertility is becoming evident. But, in the main, the great problem at present is not one of soil fertility, but of how to get enough water to make use of the fertility now present. The rainfall of this section, which varies from an actual shortage to seldom more than a meager sufficiency, makes it imperative that the best use be made of the water that falls. He who most economically gets the greatest use of the rainfall is truly the best farmer from the standpoint of production.

This bulletin is largely concerned with problems relative to the accumulation and use of the soil water. In presenting the results shown in the bulletin, we have endeavored to select that portion of our soil moisture studies which may have the most practical application. And we ask that it be read carefully and that the tables showing weather conditions be consulted in order that one may not draw the wrong conclusions from any data offered. It is imperative also that the type of soil on which this work has been carried on be kept in mind. Any variation in the soil type will probably vary—in that same degree—the results obtained. The work which we are offering has been done in the

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The data presented in this bulletin have been obtained by the North Platte Substation in cooperation with the Office of Dry Land Agriculture and the Biophysical Laboratory of the Bureau of Plant Industry, U. S. Department of Agriculture. Charts III, IV, VII, and X to XV, inclusive, are reproductions of regular soil moisture charts from the Office of Dry Land Agriculture.

The author is indebted to Messrs Fritz Ullrich, S. B. Noland, and V. V. Burr for assistance rendered in taking soil samples.

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field under field conditions and has been subject to the same detrimental or favorable factors that are common to all fields under like conditions.

It is not our aim in offering this work to teach actual farm practices affecting crop production, but to discuss underlying principles and show the effect of certain conditions. The application of these principles to the farm practices must be left to the farmer. We can show that a certain surface condition is more efficient than some other condition in catching water from rains. We also show that weeds use the water. It is left to the farmer to apply the principles. He may stack his grain and plow his stubble ground, or he may use the disk after the binder. If he can kill the weeds and get the surface in condition to hold moisture by either method, he has applied the principle. Local conditions on the farms vary so much with locality that it would indeed be hard to discuss the practices. In one section the problem would be to increase the yields of grain for the market and in another it would be to get feed for live stock. In order to bring farm practices up to the point of greatest efficiency, it is essential that the farmer understand the conditions under which he is farming and the principles affecting the practices. A thoro knowledge of the prevailing weather conditions, soil conditions, and nature and requirement of crops is essential. He can then work out the most economical practices.

From the standpoint of storing moisture in the soil, we have found summer tilling, which is clean cultivation without any crop for a season, the most ideal way in which to store moisture. When the rainfall of a season is insufficient to produce a profitable crop, it may be better to summer till than crop every year and thereby store a small portion of one season's rainfall to use with the rainfall of the following season for the production of a single crop. In other words, "to use not two years' rainfall for one crop," but rather a small portion of the first year's rainfall, added to a somewhat larger portion of the second year's rainfall for the crop. Our investigation shows that it is only under favorable conditions that as much as 33 per cent of the rainfall of one season can be carried over to the next, and that during the most unfavorable season only 10 per cent was carried over. Probably not more than 60 per cent of the second year's rainfall is utilized by the growing crop, and it is probably safe to assume that considerably less than one year's rainfall is fully utilized for crop production under the best system of summer tillage. Summer tilling is a system that has been practiced for a long time in the drier sections of the country. Altho this method of utilizing moisture is seemingly an exceedingly wasteful one, it is probably the best one devised for some crops, soils, and climatic conditions. It is obvious that it will hardly be profitable to summer till a shallow soil, for in such soils the effect of cultivation is of little value in storing water. Where there is a layer of hardpan, gravel, rock, or sheet water close to the surface, the amount of water which the shallow layer of soil above this stratum will hold is so limited that probably one good rain would saturate it. It is useless, therefore, to keep it clean cultivated thru an entire season for the purpose of storing water. Crops grown on this type of soil are almost entirely dependent on seasonal rainfall because of the very limited amount of water which so shallow a soil can hold. We cannot store sufficient water in so shallow a soil to carry the crop thru a long dry spell. As soon as the moisture stored in the soil is used, crops will suffer or die, according to the duration of the drouth. On the deeper soils, however, which prevail over the greater portion of the central and western part of the State, it is possible under normal weather conditions to store a considerable amount of moisture as a safeguard to the crop against drouth.

Where it is not desired to summer till, the same principles should always be applied. The preparation of the seed bed for a crop should begin as soon as the preceding crop is off the ground. Usually, the longer the seed bed is prepared and kept in proper condition, the greater is the amount of water stored. The seed bed will also be firmer and in better condition for the crop. Judgment must always be used in doing the work. If a soil is inclined to blow, keeping the surface bare and cultivated for any considerable time might be detrimental. If the soil is heavier, it can be cultivated with a clean surface without danger. If the soil is so dry that plowing requires an extra amount of expensive labor, it is probably better to disk. All of these, together with available horse power and help and the amount of urgent work on hand, are local problems which only the farmer can solve. Too much labor put on a field may be unprofitable. The aim should be to use such tools and do the work at such a time as to obtain maximum water storage and a compact seed bed with the lowest expenditure of labor.

The principles of storing water may be summarized in a few sentences. The surface should be kept in condition to catch the rains. It should be cultivated to keep it loose and rough, thus reducing evaporation and preventing blowing. The weeds should be kept down so far as possible both before and after seeding, to prevent their use of water.

Crops which will withstand considerable drouth or escape drouth by maturing early are recommended.

Live stock as a medium for marketing the crop, and to insure an income during unfavorable years, is essential to the success of a dry-farmer.

This bulletin is concerned with problems relating to a greater use of the water that falls. Results of tests made relative to other phases of crop production in this section are given in Bulletin 135 of this Station.

SUMMARY.

1. The maximum amount of water that the soil on the North Platte, Nebr., Substation farm will hold under field conditions is from 16 to 18 per cent of its dry weight.

2. The minimum point to which crops can use the water from the soil for growth is about 7 to 8 per cent based on the dry weight of the soil. In other words, water in the soil above 7 or 8 per cent is available for plant use.

3. Summer tillage is the most efficient means of storing water in the soil.

4. The amount of water that can be stored in the soil in one year by summer tillage is influenced by a number of factors. On the same soil it is largely governed by the amount and distribution of the rainfall, the effectiveness of the tillage, and the presence or absence of a growing crop.

5. From 10 to 33 per cent of the seasonal rainfall has been stored annually by summer tillage at the Substation during the past six years.

6. In favorable seasons the soil has been practically filled with water to a depth of six or seven feet by summer tilling.

7. During the most unfavorable year the best summer tilled land accumulated water to a depth of only three feet.

8. The distribution of the rainfall is almost as important from the viewpoint of storing water as the total amount of rain.

9. Water is accumulated most rapidly when the rains are so frequent that the surface is still wet from one rain when another comes.

10. An inch of rain falling on a very dry surface will seldom wet down more than six inches on this type of soil.

11. A rain of one-half inch is of no value in storing water, unless it comes while the surface is still fairly moist from a preceding rain.

12. Water is carried into a moist soil much more rapidly than into a dry soil.

13. A cultivated surface will retain more water from a rain than a surface not cultivated.

14. The faster the rain falls, the greater is the difference between the amount of water held from a rain by a cultivated surface and that by a surface not cultivated.

15. Plowing seems to be better than disking for accumulating water in the soil.

16. Disking small grain stubble to kill weeds and stir the surface has generally been effective in accumulating water in the soil.

17. A mulch of several inches of hay or straw is more efficient than a soil mulch in storing water.

18. Corn, oats, spring wheat, and barley use water from the first four or five feet of soil.

19. Winter wheat uses water to a depth of six or seven feet.

20. Corn grown in rows and cultivated does not dry the soil so thoroly as do the small grains.

21. The indications are that plants obtain water from the soil by the growth of the plant roots into the moist soil. Very little water is brought to the plant roots by capillary movement.

22. Under normally favorable conditions, growing vegetation is a greater factor than surface evaporation in removing water from soil which previously has been filled with water.

23. Weeds are frequently the most effective agents in removing available water from soils and in preventing the storage of water for the use of other plants.

24. A mulch three inches deep is more efficient in reducing surface loss of water during a prolonged dry spell than a shallower mulch.

25. Alfalfa, once well established on this type of soil, will obtain water from the sheet water where it is within twenty to thirty feet of the surface.

26. Capillarity is an effectual agent within certain limits, when operating close to a supply of free water. It may be an important factor in crop production where sheet water is close to

the lower limits of the soil zone occupied by the roots of the crop.

27. Away from a source of free water and in a soil partially dry, capillary movement has not been detected.

28. Water supply by capillarity is not an important factor in crop production on Nebraska upland soils.

29. The indications are that it requires almost twice as much water to produce one pound of dry matter in small grain in an unfavorable season as is required in a favorable season.

30. A year that is unfavorable for small grain is not necessarily unfavorable to corn, as the drouth which injures one may not extend into the most rapid growing period of the other.

THE STORAGE AND USE OF SOIL MOISTURE.

Studies relative to soil moisture have been carried on at the Substation since the spring of 1907. The purpose in starting the work was to determine the most efficient and economical methods of storing water in the soil, the amount of water required to produce crops, and to study the use or loss of water from the soil.

GENERAL CONDITIONS.

Part of the land used in making these studies is bench or second-bottom land, and part is table-land. The soil on the table-land is similar to that on the bench. On the bench land, sheet water is only twenty to forty feet below the surface. Subirrigation takes place on the bench land with deep-rooted plants like alfalfa, but has not been found to affect any other crops. On the table-land, sheet water is from 200 to 250 feet below the surface, and crops cannot get water by subirrigation. This absolute dependence of the crop on surface precipitation gives the best conditions for the study of soil moisture.

TYPE OF SOIL.

The soil on the farm is a fine sandy loam, commonly known as loess. The native vegetation is mainly buffalo and grama grasses. The soil is free from gravel and is easily tilled. The mechanical character of the soil is fairly uniform to a considerable depth, the most noticeable change being less organic matter in the subsoil, indicated by a change in the color of the soil. This change in color begins in the third or fourth foot. Mechanical analyses have been made to a depth of three feet.

The following table gives the results of eight analyses:

TABLE 1.—*Mechanical composition of upland soil at North Platte, Nebr.*

ANALYSES MADE BY THE BUREAU OF SOILS, U. S. DEPARTMENT OF AGRICULTURE.

Depth of sample	Organic matter	Fine gravel	Coarse Sand	Medium sand	Fine sand	Very fine sand	Silt	Clay
Feet	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	2.1	0	.1	Tr.	1.5	52.5	36.1	10.5
2	1.0	Tr.	.0	.0	1.4	50.8	36.1	11.9
3	.8	0	.1	.1	9.2	43.2	34.0	13.3
1	1.7	0	.3	.1	4.3	48.9	38.6	7.3
2	.3	0	.2	.1	2.7	55.4	32.5	9.1
3	.2	0	.0	.1	1.6	58.2	30.4	10.0
1	.9	0	.3	.1	2.1	51.0	36.1	10.3
2	.9	0	.1	.2	12.3	37.8	40.6	8.6
3	.4	0	.1	Tr.	3.6	42.9	42.3	10.5
1	.7	0	.1	.1	5.8	43.8	43.2	6.3
2	.5	0	.1	.1	5.0	44.7	42.0	7.5
3	1.0	0	.1	.1	8.2	42.7	39.2	8.9
1	2.4	0	.2	.2	6.9	43.1	42.8	5.8
2	.5	0	.1	.1	6.0	43.4	42.7	6.7
3	.6	0	Tr.	.0	4.4	40.7	45.8	8.1
1	.5	0	.7	.3	10.1	43.5	35.8	9.3
2	.8	0	.2	.3	8.3	42.6	37.1	11.2
3	.7	0	.1	.1	5.6	44.0	36.6	13.3
1	1.0	0	.2	.2	3.6	42.8	43.6	9.2
2	.9	0	.1	.1	6.0	46.3	36.4	10.8
3	.8	0	.1	.1	4.1	46.9	35.3	13.1
1	1.0	0	.4	.2	14.1	38.7	38.4	7.5
2	.8	0	.4	.2	6.6	45.5	36.1	10.8
3	.2	0	.1	.1	4.0	49.6	31.2	14.5

From Table 1 we note that the soil has a low per cent of all material coarser than very fine sand. This, with the low per cent of organic matter, would indicate that the soil would bake or crust badly. However, the soil is easily tilled, this being due probably to the correspondingly low per cent of clay and the comparatively large per cent of very fine sand. Little trouble has been experienced with the soil baking or crusting badly except in the spring of 1912. After the melting of the heavy snow late in the spring of 1912, the soil crusted badly and cracked to a depth of several inches.

In considering the work given in this bulletin, it is important that one should not lose sight of the character of the soil on which the work was done. It is not probable that the same results will be obtained upon soils of widely different character.

DEPTH OF SAMPLING.

When the work was started, samples were taken to a depth of only three feet. As the work progressed, longer tubes for sampling were procured, until samples were taken to a depth of fifteen feet. The reason for the deeper sampling was to find a point where the moisture content remains constant, where it would not be affected by the tillage or by growing crops. It was necessary to do this deeper sampling in order to determine how far the moisture from the surface would move downward, and whether water left in the soil below the reach of the crops for one season might not move upward into the feeding zone of the following crop. We have found from a large number of samplings that frequent deep sampling is not necessary on this "hard" land, under continuous cropping, except during seasons of abnormally frequent and heavy rains. The available water is confined to a few feet of soil at the surface. Our aim is to sample deeply enough to include the whole zone in which the movement of water affects crop growth.

WATER IN THE SOIL.

In order better to understand the work presented in this bulletin, a brief discussion is given of the water found in the soil.

Water is found in the upper strata of the soil in three conditions:

1. That which is absorbed by the soil particles from the water vapor of the air—called hygroscopic water.

2. That which is held by surface tension, as more or less

thickened films around the soil grains, and in the small pore spaces between the soil particles—called capillary water.

3. That which is being drawn downward thru the soil by the pull of gravity—called gravitational water.

HYGROSCOPIC WATER.

Hygroscopic water is that which an absolutely dry soil will absorb when exposed to a moist atmosphere. The amount of water a soil will absorb from a saturated atmosphere depends mainly upon the temperature and the type of the soil. The finer the soil particles, the more water they will absorb. This water is held in the soil as thin films around the soil particles. It is of no value in furnishing water to agricultural plants. It probably has a beneficial action in bringing into solution some of the plant food material held in the soil, on account of its close contact with the soil particles. From determinations that have been made in the laboratory, and from studies made under field conditions, the conclusion has been reached that plants are not able to use this moisture for growth.

CAPILLARY WATER.

Capillary water, or that which is held against gravity in the small pore spaces and adhering as thickened films to the soil particles, is the source of supply to growing vegetation. This water may move in any direction in the soil, but its movement is slow. It moves thru the soil much the same as oil moves along a lamp wick. As some portion of the soil becomes drier, the films of water around these soil particles become thinner, exert a greater force, and consequently draw some water from the adjoining particles of soil. The films around these particles in turn draw from the next and so on, moving the water slowly from the more moist to the drier portion of the soil. If the loss of water is checked, the movement of water will cease as soon as the soil particles at the drier portion have received sufficient water so that they can no longer exert a stronger force than the adjoining particles.

From the standpoint of crop production we are interested almost wholly with the water that is held by capillary force within the soil zone occupied by the plant roots. The movement of water thru the soil by capillarity is so slow that it is practically useless in bringing water from a lower soil area for the use of a growing crop. The rapid use of water by crops, especially during seasons of drouth and increased transpiration, requires more water than can be supplied by capillarity. Plants will suffer and die under extreme conditions after having used the available water within reach of the roots, even tho there is additional water in the soil immediately below. Under a system of alternate cropping and summer tilling we have found an accumulation of water just below the feeding zone of the crops. During dry seasons when the crops have been suffering for moisture this water did not move upward by capillarity in sufficient quantity to be of material benefit to the crop. There is no evidence that it will replace to any considerable extent during an interval of even several months the water removed from an upper soil zone. This is true on soils separated by a considerable distance from a supply of free water, as sheet water. Where there is a constant supply of free water, there will be a rather rapid movement of water for a certain distance thru the soil, depending upon the type and compactness of the soil.

The frequent, rapid drying of several inches of soil at the surface has in some cases been accounted for thru the quick movement of water by capillarity. It seems to indicate a more rapid movement than is found in the lower soils. There is, doubtless, an increased movement due to higher temperature, but the greater circulation of air in the soil near the surface is a large factor in the rapid drying of surface soils.

GRAVITATIONAL WATER.

As a soil becomes more and more nearly saturated, it reaches the point where gravity exerts a stronger pull than surface tension. Water then begins to move downward thru the soil and tends to connect with the ground water or sheet water below. When the ground water is at a great depth, as it is on most of the table-lands, it is decidedly doubtful if any surface water ever reaches it. When the surface soil becomes oversaturated with water, the downward movement of the water continues until, by distributing the water thru a larger body of soil, the force of gravity is finally equalized by the capillary power of the soil.

MAXIMUM WATER-HOLDING CAPACITY OF A SOIL.

The maximum water-holding capacity of a soil is the amount of water that soil will retain against the pull of gravity. When water is added to a soil in sufficient amount, the films of water around each soil particle become thickened, and the small spaces between the soil particles filled with water. In the addition of water a point is reached where the attraction of gravity overcomes the force that holds the water to the soil particles, and the water is drawn downward into the lower soil. If no more water is added, a point is reached where the pull of gravity is equaled by the force that holds the water to the soil, and there is no further movement except by the slow action of capillarity. The amount of water in the soil at this time is termed "maximum water-holding capacity" or "saturation point."

The amount of water a soil will hold against gravity depends upon the type of soil. A clay soil composed of fine particles with very small spaces will retain more water than a coarser, sandier soil composed of larger particles and larger spaces. Also, the amount of humus, or decomposed organic matter, in the soil influences the water-holding capacity. The more humus in the soil, the more water it will hold, providing the soil particles are of similar size.

MINIMUM POINT OF EXHAUSTION BY THE PLANT.

The minimum point of exhaustion of water from the soil by the plant is the point at which the force exerted by the plant in obtaining water is equaled by the attraction of the soil for the water. At this point the plant can obtain no more water from the soil and will suffer until water is supplied. The minimum point of exhaustion is in direct correlation with the maximum water-holding capacity of the soil. A fine soil that has a high water-holding capacity will exert a strong resistance to the use of water by the plant, while a sandy soil, with a lower maximum, has a correspondingly lower minimum of water which is not available for the use of the plant. The water held in the soil below the minimum point of exhaustion by the plant is called "nonavailable water." Some water may be taken from the soil below the minimum point, but not in sufficient amount or rapid enough to promote plant growth or even to sustain life for any considerable period of time.

From an agricultural standpoint, only the available water is of value. The available water in the soil is the amount that the farmer has to use, in addition to the rainfall, to produce crops.

In order to interpret results from moisture data, the maximum water-holding capacity and the minimum point of use should be known. These points rise or fall, depending upon the composition of the soil. In the following table we give the data covering these two points:

TABLE 2.—*Showing maximum water-holding capacity of this type of soil, 1908-1909.*

HARD TABLE-LAND. BUFFALO GRASS SOD.

	Depth	1908					1909				
		Sept. 9	Sept. 17	October 1	October 9	October 20	March 19	April 22	June 1	July 30	Sept. 22
	Feet	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
	1	6.7	9.1	14.8	12.4	20.6	22.4	16.6	22.6	13.7	13.7
	2	7.4	17.9	15.7	16.0	19.7	16.3	16.8	19.1	14.8	14.1
	3	7.4	19.3	15.9	16.0	18.9	15.3	15.6	16.3	15.5	14.2
	4	7.4	19.7	16.2	15.7	17.9	14.6	15.9	16.0	15.8	14.3
	5	8.5	23.7	19.3	19.6	19.4	17.5	16.0	16.6	18.7	17.5
	6	9.1	23.0	19.5	20.1	19.2	18.0	15.0	17.7	23.0	17.9
	7	9.9	22.2	18.9	19.0	18.1	17.1	15.6	16.6	19.5	17.8
	8	11.8	21.1	18.2	17.5	18.2	16.3	14.0	15.2	19.7	17.3
	9	11.8	21.5	17.3	16.5	15.4	14.4	12.4	14.8	17.4	15.2
	10	11.2	22.9	18.3	17.0	16.0	13.9	12.3	12.8	18.5	14.9
	11	....	....	....	....	....	....	15.6	16.4	....	19.6
	12	....	....	....	....	....	....	14.1	17.7	....	18.2
	13	....	....	....	....	....	....	11.0	15.4	....	16.4
	14	....	....	....	....	....	....	14.4	15.9	....	18.3
	15	....	....	....	....	....	....	16.1	15.0	....	18.2
Average to	10	9.1	20.0	17.4	17.0	18.3	16.6	15.0	16.7	17.7	15.7

In Table 2 we give the results of a series of determinations made to ascertain the maximum water-holding capacity of this type of soil. On September 9, 1908, the amount of water present in the soil was determined. After making this determination, an excavation eight feet in diameter and one foot deep was made. A total of thirty-six inches of water was put into this to insure saturation, and the dry earth, which had been removed in excavating, was put back as a mulch. About six or eight inches of hay was put over all of this in order to reduce surface evaporation to a minimum.

Samples were taken from time to time, as shown in the table, to determine the movement of the water. We note that between the sampling of September 17 and October 9, 1908, there is a loss of 3 per cent, or a total of five inches of water. It is evident that this water moved downward, as the first foot shows conclusively that the water did not escape from the surface. This section of the soil was not sufficiently moist to lose much water. Just after the sampling on October 9, a three-inch rain fell, which explains the increased amount of water found October 20 We then find a decrease to April 22, 1909, when the upper six feet of soil have on an average about 16 per cent of moisture. There is an increased amount again when the rains start during the summer, but it drops later in the season. It would seem then that the maximum water-holding capacity of our soil is between 16 and 18 per cent. (All moisture percentages given in this bulletin are figured on the basis of the dry weight of the soil; for example, 10 per cent represents that for each one hundred units of dry soil that there are ten units of water present.)

TABLE 3.—*Minimum point of exhaustion of soil water by the crop.*

Crop	Per cent moisture in the soil					
	1st ft.	2d ft.	3d ft.	4th ft.	5th ft.	6th ft.
Spring wheat	7.1	8.0	8.2	8.5	.....	.
Winter wheat	7.4	7.1	7.4	7.4	7.4	7.8
Oats	7.9	7.7	7.7	7.7	.....	.....
Corn	8.6	9.1	8.9	9.6	.....	.....
Cane	8.0	8.4	8.1	8.3	.....	.....
Barley	7.1	6.7	7.3	7.1	.....	....

Table 3, giving the minimum point to which crops can use the water from this soil, was obtained by averaging a considerable number of minimum points shown for several years in fields where various crops were growing. No minimum points are shown below four feet for any crop except winter wheat. The other crops shown did not completely dry the soil below four feet. The percentages shown indicate that the minimum point of available water in this soil is from 7 to 8 per cent.

STORING WATER IN THE SOIL BY SUMMER TILLAGE.

Storing water in the soil consists of getting the water into the soil and then preventing its escape. Summer tillage has been the most efficient of all methods of storing water. This is to be expected, since the surface is always in condition, if the work is properly done, to catch any rain that falls and to check evaporation from the surface. Also on properly summer tilled land there are no weeds or other vegetation allowed to grow and use the water from the soil. In the following tables are given data relative to the accumulation of water in the soil.

TABLE 4.—*Storing moisture by summer tilling.*

PER CENT MOISTURE IN THE SOIL.

Spring wheat, 1907; summer tilled, 1908.

Date sampled		Aug. 24, 1907	April 4, 1908	May 7, 1908	June 3, 1908	July 7, 1908	Aug. 5, 1908	Sept. 11, 1908
Depth in foot sections	1	7.8	14.6	19.7	21.1	22.5	16.1	14.8
	2	8.2	11.8	13.2	18.3	18.4	16.8	15.9
	3	7.9	8.8	9.5	13.5	17.5	16.3	15.6
	4	8.6	10.7	11.7	12.0	16.2	16.0	16.4
	5	12.6	15.5	14.2	16.2	17.8	18.6	20.0
	6	13.9	15.0	14.4	15.3	15.7	16.9	18.1
Average		9.8	12.7	13.8	16.1	18.0	16.8	16.8

Oats, 1908; summer tilled, 1909.

Date sampled		Sept. 18, 1908	Mar. 30, 1909	Apr. 12, 1909	May 18, 1909	June 29, 1909	Aug. 25, 1909	Oct. 5, 1909
Depth in foot sections	1	8.7	18.4	18.1	16.4	19.6	18.3	15.0
	2	9.0	14.4	15.3	15.0	18.3	17.8	15.7
	3	9.0	9.3	9.6	9.7	17.1	16.8	15.2
	4	9.6	11.2	10.5	11.2	16.5	17.2	16.2
	5	14.7	16.1	15.3	15.6	18.5	20.4	19.6
	6	14.2	15.3	14.0	14.5	15.5	18.5	18.1
Average		10.9	14.1	13.8	13.7	17.6	18.2	16.6

TABLE 4.—*Storing moisture by summer tilling—Concluded.*

PER CENT MOISTURE IN THE SOIL.

		Cane, 1909; summer tilled, 1910.			Oats, 1910; summer tilled, 1911.			
Date sampled....		Sept.17, 1909	Mar.20, 1910	Aug. 8, 1910	April 1, 1911	June 13, 1911	Sept.11, 1911	Oct. 21, 1911
Depth in foot sections	1	7.8	15.4	13.3	11.7	14.9	16.9	19.6
	2	7.9	11.3	12.8	8.0	11.7	15.1	17.7
	3	8.2	9.1	11.7	8.6	7.6	10.8	13.1
	4	8.5	8.2	9.8	12.3	11.0	10.9	11.1
	5	9.1	7.8	9.0	13.0	12.4	15.1	15.0
	6	9.2	9.2	10.0	14.0	13.7	16.6	13.8
Average		8.4	10.1	11.1	11.3	11.9	14.2	15.1

		Spring wheat, 1910; summer tilled, 1911.			Winter wheat, 1911; summer tilled, 1912.			
Date sampled.....		Mar.29, 1911	June 13, 1911	Sept.21, 1911	Apr. 25, 1912	June 15, 1912	Aug. 8, 1912	Nov. 12, 1912
Depth in foot sections	1	10.7	14.3	15.4	20.8	18.1	19.1	17.2
	2	11.5	11.7	13.9	16.3	16.3	16.6	16.1
	3	7.7	8.1	11.7	9.8	15.0	14.7	15.4
	4	8.8	8.5	7.9	9.3	11.1	13.7	14.2
	5	12.5	12.0	11.2	9.7	10.4	11.0	12.0
	6	14.4	13.6	13.5	8.9	9.2	10.0	9.9
Average		10.9	11.4	12.2	12.5	13.3	14.2	14.1

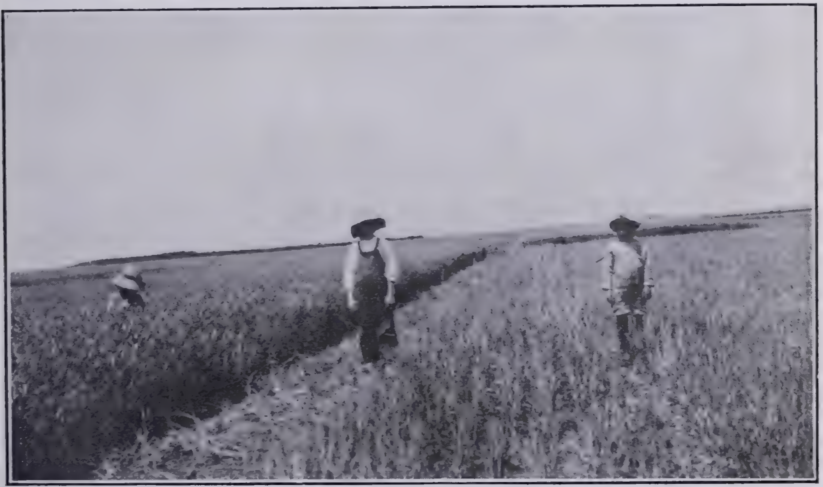
In Table 4 are given the data obtained from samplings made at various times in the fields. The first field given was in spring wheat in 1907, and was summer tilled in 1908. Soon after harvest, 1907, the soil contained an average of 9.8 per cent of water in the upper six feet. At seeding time in 1908 the soil contained, to this depth, an average of 16.8 per cent of water, a gain of 7 per cent, or about 6.5 inches of water. The rainfall during the interval was 19.7 inches, of which about 33 per cent was stored.

The next field shown was in oats in 1908 and summer tilled in 1909. In the fall of 1908 the soil was dry to four feet. During the winter the first two feet became filled with water. During the entire period 5.5 inches of water were stored from a total rainfall of almost twenty-three inches. About 24 per cent of the seasonal rainfall was held.

The third field given was in cane in 1909 and summer tilled in 1910. Almost 2 per cent of water accumulated in the upper two feet of soil during the winter. During the entire summer from

March to August only 1 per cent of increase is shown in the moisture content. During the entire period from harvest to seeding date, only 2.5 inches of water were accumulated. The rainfall during the period was 12.2 inches, of which 21 per cent was retained. Even with this small amount of stored water, this field and another that was summer tilled with much the same results in 1910, and both sown to winter wheat, were the only fields on the Station that produced any small grain in 1911.

The fourth field shown was in oats in 1910 and summer tilled in 1911. An increase of 4 per cent is shown in the moisture content. This makes about 3.7 inches of water, which was 23 per cent of the rainfall of 15.8 inches.



Plat D on left. Summer tilled, 1912—yield of winter wheat 1913, 26.8 bushels. Plat C on right. Continuous cropping—yield 2.2 bushels.

The fifth field shown was in spring wheat in 1910 and summer tilled 1911. This field shows an increase of only 1.3 per cent of moisture during the summer. This is only 1.25 inches of water out of a total of 12.1 inches, or only 10 per cent of the rainfall.

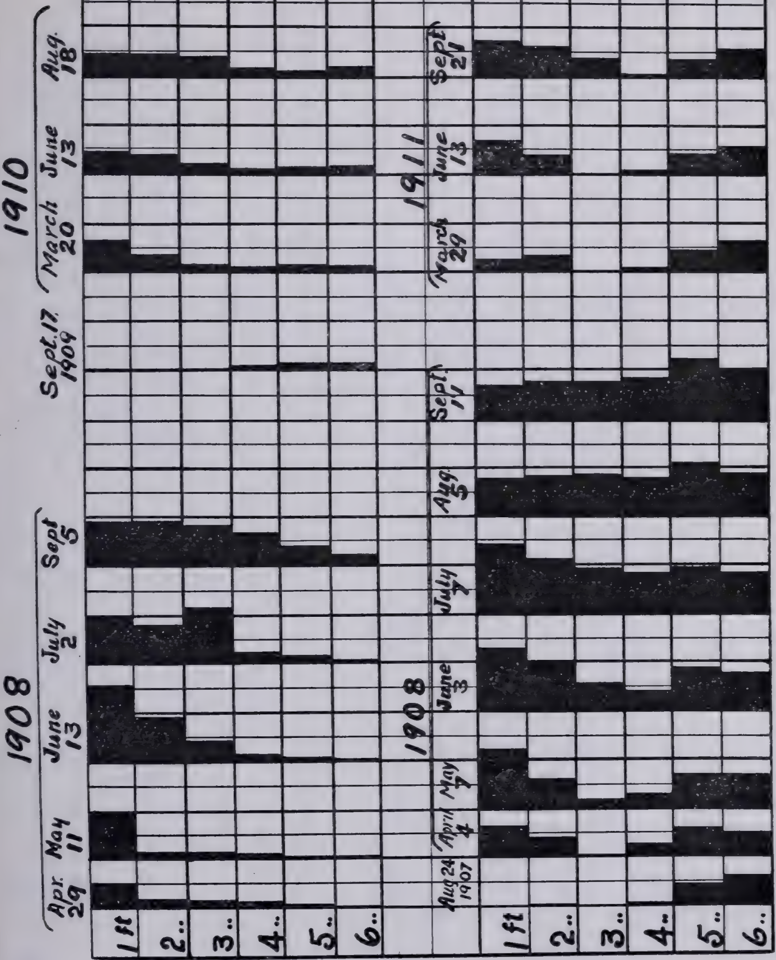
The last field shown in the tables was in winter wheat in 1911 and summer tilled in 1912. The first sampling was made some considerable time after the field had been disked, and just after a rain of an inch, which was caught and retained in the upper two feet. Between the first and last sampling about 1.5

inches of water were retained from a rainfall of 12.7 inches. This was about 12 per cent of the total rainfall. It will be noted that this field contained almost as much water the middle of June as it did at the close of the season. On June 15 it had available moisture to a depth of five feet. The field was in good condition, from a moisture standpoint, to seed to a field crop such as cane. Or, if one were preparing to seed alfalfa, the early spring cultivation not only prepares the seed bed and gets rid of weeds, but accumulates moisture to start the crop. From the data given in this table, there have been two years, 1908 and 1912, when water was accumulated to a depth of several feet in time for seeding alfalfa by the middle of June. A stand of alfalfa is much more certain with several feet of moist soil for a seed bed than where only the surface is moist.

From the table and the discussion of it, we find that the amount of water which can be stored varies greatly with the different years. The per cent of the total rainfall held varies from 10 to 33 per cent. During the summer of 1908, there were eight rains of more than one-half inch each, three of which were more than an inch each. There were also rainy periods when light rains came so close together that the surface soil would be wet from one rain until the next and, therefore, even a small rain would penetrate below the surface. During the summer of 1910, only three rains came of more than one-half inch, two of which were over an inch. The season of 1911 was better from the standpoint of total amount of rain, but the distribution was such that the moisture could not be held. During dry seasons, with the high rate of evaporation and extremely hot surface soil, a half inch of rain may be lost before it gets into the soil deep enough to be retained, if it comes as an isolated shower. Where the surface is dry, a rain of less than one-half inch is of no value whatever in storing water, tho it may be of great value to the crops. A half inch of water will not get thru the loose mulch on the surface unless the mulch is still moist from a previous rain.

It is also noted from the tables that the water content was not increased below three feet in 1910 or 1911. In 1912 it was increased to five feet, while in 1908 and 1909 the soil was filled as deep as the samples were taken. The weather records for the years under consideration show the causes of the variation in the results of storing moisture as shown in Table 4. The table shows that during some seasons, when the rainfall is low or poorly distributed, it is impossible to accumulate much water in the soil by summer tillage.

CHART I.—STORAGE OF WATER IN SOIL BY SUMMER TILLING



From top to bottom of chart each division represents one foot-section of soil. From left to right each division represents 5 per cent of available moisture.

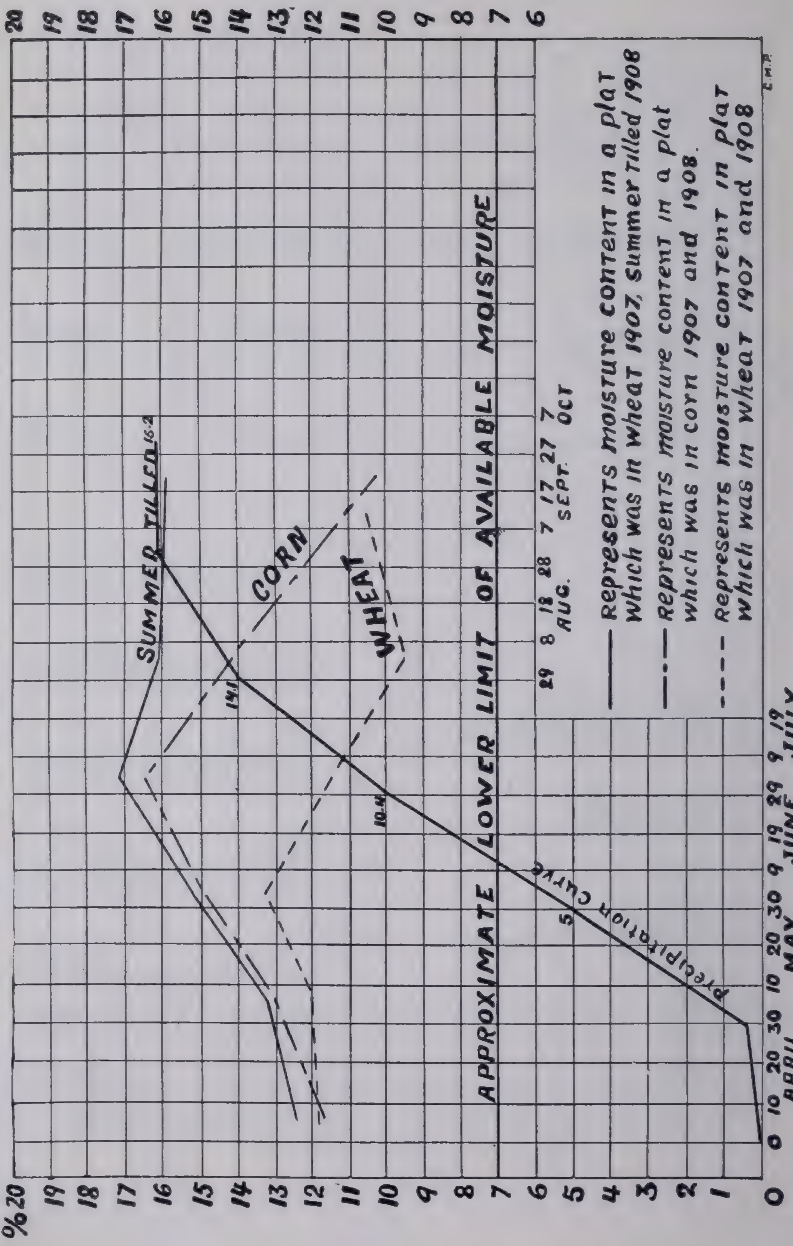


CHART II.—AVERAGE PER CENT OF MOISTURE IN FIRST 6 FEET OF SOIL, 1908.

Charts I to IV show graphically the amount of water stored by summer tilling. Chart I shows the work done in four fields. Two of these fields were summer tilled during the summer of 1908, which was a good year for storing water. The other two fields were summer tilled during dry seasons. In this chart the base line represents 8 per cent, or practically the lower limit of available water. All water added to the soil above this point and held within reach of the plant roots can be used by the crop. The foot sections of soil are shown on the left of the chart. This chart further illustrates the fact that the amount of water which can be stored by summer tilling in this soil is largely governed by the amount and distribution of the precipitation.

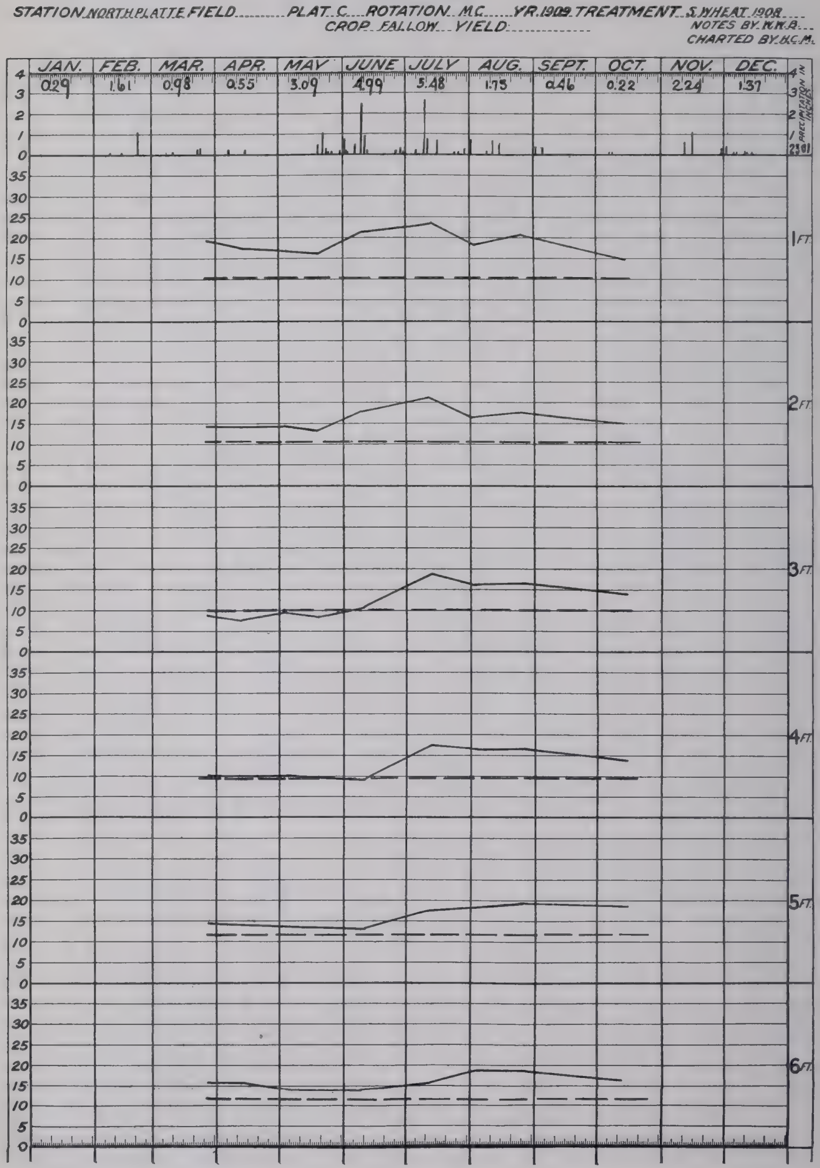
Chart II shows the average amount of water in the upper six feet of soil in three fields, and the amount of precipitation during the interval.

Each square on the chart, as we go upward from the bottom, represents 1 per cent of water in the soil or one inch of rain. As we go from the left to the right on the chart, a square represents a period of ten days time. According to work done by Drs. Briggs and Shantz of the Bureau of Plant Industry, the approximate lower limit of moisture available for plant growth is somewhat too low as represented on this chart.

In the spring each of three fields here represented had about the same average water content. The water content of the field sown to wheat increases slightly, under the heavy May rains, until the latter part of May. After this date the crop not only uses the rain that falls, but draws on the soil for almost four inches of stored water. After harvest an increase is shown, and at the last sampling the wheat and cornfields have about the same amount of water. That the wheatfield did not gain in water content as rapidly in the spring as either of the other fields was due to the fact that the crop was already using a good portion of the rain that came.

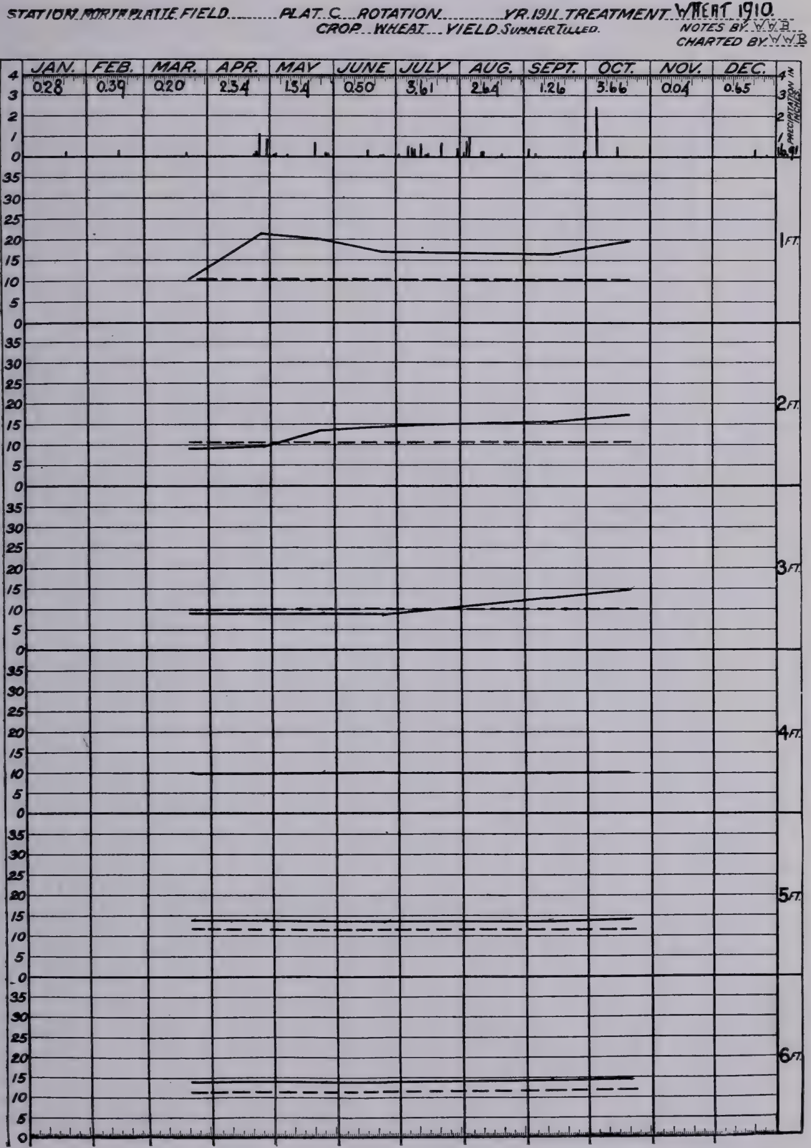
It will be noted that the field listed to corn increased in water content almost as rapidly to July 1 as did the summer tilled field. Up to this time the corn plants, few in number and small as compared with the wheat, were not making much demand for water. Almost five inches of water had been retained from the rains up to this time. At this period the corn began to use more water and not only used the rain that fell, but used more than five inches of water that had been stored in the soil. The summer tilled field retained this and remained thru the winter with practically all the water the soil would carry in the upper six feet.

CHART III.—STORAGE OF MOISTURE IN THE SOIL BY SUMMER TILLAGE.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

CHART IV.—STORAGE OF MOISTURE IN THE SOIL BY SUMMER TILLAGE.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

Chart III gives further data concerning the effects of summer tilling. On the right hand side of the chart beginning at the top are shown first the spaces showing rainfall in inches, and rainfall for the year. Below that are shown the depth which each section of the chart represents, from one to six feet. On the left of the chart is shown the per cent of water. Each section of the chart is divided by minor lines. The spaces between these lines represent five per cent of water in the soil. The heavy, broken horizontal lines represent the "wilting coefficient" as defined by Briggs and Shantz.* The wilting point as indicated on these charts is probably somewhat high as is shown by field results. All water over 8 per cent is available for crop use in this soil. The chart is divided to show the different months and days of the month. The perpendicular lines near the top represent the amounts of various rains on various dates. The total for the month is shown in figures at the top of that section. The heavy, solid, horizontally-drawn lines represent the moisture content of the soil at that particular depth. (This explanation will serve for all charts of this kind used in this bulletin.)

It will be noted from the chart that at the first sampling the first foot of soil was filled with water and some water was available in the second foot. Below that the soil was dry. The chart shows several heavy rains between the sampling in June and that done in July. The June sampling showed that the third foot was beginning to receive water and that the fourth foot had not yet received any water. In July the sampling was done so soon after the heavy rain that the first three feet had more water than they would hold. Water had penetrated to five feet. At the time of the first sampling in August, the first six feet were filled to the maximum carrying capacity. Some loss is shown during the latter part of the season, which was very dry.

Chart IV shows the effect of summer tilling during a less favorable year (1911) than shown in Chart III. The samplings this year are not frequent enough to show all the fluctuation in the moisture content of the first foot. The chart does show, tho, the ultimate results. There were two rains of more than one inch during the season. The effect of the first one is seen at the second sampling. All the water that was held is still in the first foot. At the next sampling an increase of water is shown in the second foot. The third foot does not show any increase in water content until July, and it is not entirely filled with water at any time during the season. The moisture chart for the fourth, fifth, and sixth foot sections makes a straight line for the entire season, showing that there was no change in the amount of water in these sections during the entire season. The chart further proves that the amount and distribution of the rain was such that no great amount of water could be stored. The water did not get into the soil to such a depth that it could be conserved.

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* Bulletin No. 230 of the Bureau of Plant Industry, U. S. Dept. of Agr., on "The Wilting Coefficient for Different Plants and Its Indirect Determination," by Briggs and Shantz.

DEPTH TO WHICH WATER HAS BEEN STORED IN ONE SEASON.

The depths to which water can be stored in a given length of time depends upon several factors: the type of soil, the underlying strata, the amount and distribution of the rainfall, the amount of water already in the soil at the beginning of the interval, and weather conditions.

A light sandy type of soil will absorb water much more readily than a heavy type of soil. The same amount of water will be distributed thruout a greater area in a light soil than in a heavy soil. The maximum carrying capacity is lower in a light soil. Furthermore, there is less resistance to the downward movement of water thru a light soil. A shallow soil overlying a stratum that is practically impervious to water or a layer of coarse gravel or sand may require only a small amount of water to bring it up to its carrying capacity. In this case any additional water would be lost.

It is obvious that the amount of precipitation and its distribution is an important factor in determining the depth to which water can be stored in a given interval. Where only a small seasonal rain comes, a relatively small amount will be held, and consequently a relatively smaller portion of the soil will be moistened. An isolated rain even of a considerable amount falling on a hot, dry surface is largely lost. The distribution of the rainfall, therefore, plays an important part. It is during rainy seasons where rains are rather frequent that moisture is most easily accumulated.

In the following table are given data to show the depth to which water has been accumulated during each of six years. Each year two samplings are shown,—one at the beginning of the season, the other at the close,—and in every case the field was summer tilled:

TABLE 5.—*Depth to which water has been stored in one year.*

PER CENT MOISTURE IN THE SOIL.

Depth	1907		1908		1909		1910		1911		1912	
	May 2	Sept. 12	April 23	Sept. 5	Mar. 27	Sept. 16	Mar. 20	Aug. 1	Mar. 29	Sept. 21	April 5	Nov. 5
Feet												
1	15.1	18.4	12.9	16.8	18.6	14.9	15.4	13.3	10.7	15.4	13.8	17.2
2	14.8	17.0	9.6	17.0	13.0	15.0	11.3	12.8	11.5	13.9	10.3	16.1
3	14.3	15.7	9.5	16.5	10.7	17.6	9.1	11.7	7.7	11.7	9.8	15.4
4	....	15.0	9.1	14.6	9.8	14.7	8.2	9.8	8.8	7.9	9.3	14.2
5	...	13.7	8.5	11.9	8.6	14.6	8.8	9.0	12.5	11.2	9.7	12.0
6	....	14.6	8.3	10.3	9.6	14.5	9.2	10.0	14.4	13.5	8.9	9.9
7	....	....	....	9.1	10.8	15.6	9.6	10.6	13.3	11.6	9.0	9.2
8	....	....	....	8.7	13.3	14.9	9.1	12.6	11.4	10.1	9.1	8.4
9	....	....	....	8.4	14.3	15.5	10.7	12.8	10.9	9.7	9.0	9.0
10	....	....	....	7.9	13.1	13.3	10.8	14.4	10.9	9.7	9.1	8.7
Av. 6	....	15.7	9.6	14.5	11.7	15.2	10.3	11.1	10.9	12.3	10.3	14.1
Av. 10	....	....	....	12.1	12.1	15.0	10.2	11.7	11.2	11.4	9.8	12.0
Rainfall during period, in inches			13.9		15.7		5.8		11.2		12.7	
Amount held in upper 6 feet..			4.6		3.3		1.0		1.1		3.4	
Per cent rainfall held in upper 6 feet			33.0		21.0		17.0		10.0		27.0	

We have used a summer tilled field because summer tillage is more effective than any other farm practice in storing moisture. In the lower portion of the table are given the rainfall during the intervals, the number of inches of water held in the upper 6 feet of the soil, and the per cent of the total rainfall held in the upper 6 feet. In some cases, which is true in 1909, water was accumulated below 6 feet, but we have not tried to show this in the per cent since below 6 feet the soil is not as uniformly dry at the first sampling as it is above 6 feet. This is shown in two fields used in 1910 and 1911. It is evident that in either of these years no water was accumulated below 6 feet, and yet there is no agreement between the first and second samplings on these fields. This is probably due to the sampling in different places in the field and in one case finding more water left by the preceding crop than in the other.

It will be noted that for the year 1907 the first sampling was to only 3 feet. This is the depth we were sampling in the spring. At the close of the season, the soil was practically filled to a depth of 6 feet. In 1908 the spring sampling was to 6 feet, but during the season a longer tube was obtained and samplings in the fall were taken to 10 feet. During this interval 13.9 inches of water fell, 33 per cent of which has held.

In 1909 water was accumulated to a depth of 7 feet. In 1910 and 1911 water was accumulated to a depth of only 3 or 4 feet, and in neither case was the soil filled to normal carrying capacity. The rainfall of 1910 was too low, and in 1911 the distribution of the rainfall was unfavorable for accumulating water. In 1912 water was accumulated to 5 feet.

It will be noted that during these six years we have held from 10 to 33 per cent of the rainfall in the upper 6 feet of the soil. Reference to the distribution of the rainfall in the tables given under climatic data will probably explain this.

These data are taken from 5- and 10-acre fields, one of which is summer tilled each year at the Station and receives uniformly good summer tillage. It shows, however, that we cannot store moisture unless it falls in sufficient amount and with a proper distribution to get it into the soil.

EFFECT OF CONDITION OF SOIL AT SURFACE AND CHARACTER OF RAIN ON WATER RETENTION.

The condition of the surface soil has an important influence on the amount of water that will be retained from a certain rain. Water runs off much more freely from a smooth, dry surface than from a surface which has been loosened by cultivation. The smooth, compact soil has less chance to hold the water and the dry soil offers more resistance to the penetration of the water than does a soil that is more open. Where the surface has been cultivated, the water runs into the openings made by the implement used, and is held until it can soak into the soil. Where the surface has not been stirred, there are no open spaces to catch the water. As soon as the soil at the surface has been filled, it can hold no more water except as the water is removed from the surface by penetration. The water which falls above this amount will be lost as run-off unless the surface is level. Obviously the amount of run-off from any rain is governed largely by the type of soil and character of the rain. A loose, sandy soil offers so little resistance to the penetration of water that there is little run-off. The soil particles composing the sandy soil are larger than those of heavier soil, and consequently the open spaces are larger and water readily penetrates into the soil. It is only during excessively heavy rains that run-off is seen in real sandy soil. The resistance to the penetration of water increases as the soil becomes heavier or more like clay. All gradations are found, from the sand, which offers so little resistance, to the gumbo, where penetration is extremely slow. We have observed that water will stand for several days over a heavy gumbo spot, and be lost mainly by evaporation rather than by penetration; often penetrating only a few inches into the soil.

The character of the rain has also an important influence on the amount of water which will be retained from any given rain. The more rapidly the water falls on the surface the greater the run-off. During heavy, torrential rains the water falls so rapidly that it does not have time to penetrate into the soil and must be lost as run-off. The beating drops of water often puddle or clog the surface, making it more difficult for the water to enter. It is a matter of common observation that a heavy downpour of rain frequently does less good than a much lighter rain that falls more slowly. The type of rain that is really most beneficial is the rain of sufficient amount and falling slowly enough to be carried into the soil to a depth where it will not be exposed to the rapid surface evaporation.

Of equal importance with the two factors above mentioned in governing the amount of water held in the soil from any given rain, is the amount of water present in the soil when the rain comes. A very dry soil offers much greater resistance to the downward movement of water than does a moist soil. In a very dry soil the movement is so retarded and the amount of water required to moisten it so great, that the water from a single rain, coming alone, is generally held near the surface. From here it is soon lost thru the rapid evaporation which takes place at the surface. On the other hand, where the soil is already moist when the rain comes, it is much more quickly carried away from the surface, thus giving place for more water from the rain to be held at the surface. It is also distributed to lower depths in the soil and thus protected from the rapid loss at the surface. Frequent observations have been made along this line on the native sod. This is usually hard and dry. It is seldom wet more than a few inches by the rains that come singly. The lower depths receive moisture only during "rainy" or "wet spells" when a second rain comes before the moisture from the preceding rain is lost.

In the following tables are given data bearing upon these points:

TABLE 6.—*Effect of surface condition in retaining rainfall, 1908.*

PER CENT MOISTURE IN THE SOIL.

Depth	Sod land			Corn land		
	May 11	May 15	Gain	May 12	May 15	Gain
Feet						
1	16.8	21.0	4.2	18.5	20.6	2.1
2	8.7	8.6	....	11.0	16.4	5.4
3	7.3	7.6	...	9.4	9.6	....

Table 6 gives data to show the effect of the surface condition on the amount of water held. During the interval between the sampling dates 1.62 inches of water fell. This fell as three rains, the greatest of which was .86 inch and fell very rapidly. The samples were taken twenty-four hours after the last rain.

TABLE 7.—*Effect of surface condition and moisture content on storing water, 1909.*

PER CENT MOISTURE IN THE SOIL.

Depth	Brome grass sod			Corn land		
	Sept. 3	Sept. 4	Gain	Sept. 3	Sept. 4	Gain
Inches						
1-3	9.5	15.3	5.8	12.4	17.1	4.7
4-6	6.4	6.5	....	13.3	16.2	2.9
7-9	6.9	6.6	....	13.6	15.2	1.6
10-12	6.8	6.5	....	13.3	13.2	....

Table 7 shows the difference between a cultivated and uncultivated surface in retaining water. A rain of .31 inch fell slowly during the interval between the two samplings. The brome sod retained about 70 per cent of the water which fell. It was all held in the upper three inches of soil and was soon lost. The corn land held practically all of the rain and it was distributed thru nine inches of soil.

TABLE 8.—*Effect of amount of water in soil on penetration, 1909.*

PER CENT MOISTURE IN THE SOIL.

Depth	Alfalfa field			Corn land			Wheat land		
	July 7	July 13	Gain	July 7	July 13	Gain	July 9	July 12	Gain
Feet									
1	7.5	17.1	9.6	17.4	21.8	4.4	8.8	21.0	12.2
2	8.7	8.9	....	17.1	19.3	2.2	9.7	11.1	1.4
3	8.8	8.5	....	16.1	17.6	1.5	9.2	9.6	....
4	8.3	8.5	....	17.1	18.1	1.0	9.8	10.3	....

The data given in Table 8 were obtained from three fields under different crops. During the period between the samplings, over three inches of rain fell. All the water held by the soil growing alfalfa was held in the upper seven inches of the soil. In the wheat, which was grown on spring plowed land, the water moved thru the first foot of soil and a small amount into the second foot. In the cornfield the moisture content was increased below four feet. A sampling a week later showed an increase of three-fourths inch of water in the fifth and sixth foot-sections. The corn land does not show much increase in water content near the surface. It was already filled to nearly carrying capacity, and much of the water that was caught was carried to lower depths. In the alfalfa field, which was dry when the rain came, all the water retained was held near the surface. Here it was exposed to the rapid evaporation which takes place at the surface.

TABLE 9.—*Effect of surface condition and moisture content on storing water, 1910.*

PER CENT MOISTURE IN THE SOIL.

Depth	Alfalfa field—soil dry. Surface not stirred.			Corn land—soil more moist. Surface cultivated.		
	June 30	July 2	Gain	June 30	July 2	Gain
Feet						
1	6.7	14.3	7.6	10.0	21.4	11.4
2	6.9	6.6	....	10.3	13.9	3.6
3	7.1	7.3	....	10.6	10.8	....

The data given in Table 9 were obtained from sampling just before and thirty-six hours after a rain of 1.49 inches. A little more than one inch of water was retained in the alfalfa, but it was held in the upper five inches, where it was soon lost by the surface evaporation or used by the crop. The soil was so dry as shown by the first sampling that the water could penetrate but slowly into it. The corn plat shows an accumulation of more water than fell during the rain, indicating that it had caught some of the run-off from the sod land and roadway just above the field. The water acquired from the rain had penetrated into the soil in the cornfield to a depth of eighteen inches, thus getting deeply enough into the soil to escape the rapid evaporation at the surface. This shows how much more rapidly water will penetrate a moist soil than a dry soil, as well as the fact that the cultivated surface in the corn retained much more water than the dry, firm, surface in the alfalfa field.

TABLE 10.—*Effect of surface condition and moisture content on storing water, 1912.*

PER CENT MOISTURE IN THE SOIL.

Depth	Prairie sod			Cane field			Corn field		
	July 25	July 26	Gain	July 25	July 26	Gain	July 25	July 26	Gain
Feet									
1	6.8	12.1	5.3	14.8	20.4	5.6	13.5	19.2	5.7
2	6.3	6.3	....	15.0	16.3	1.3	10.5	11.3	.8
3	6.0	6.4	....	13.9	14.9	1.0	13.2	12.7	....
4	6.7	7.5	...	13.6	13.5	...	15.3	14.8	....

These data in Table 10 were obtained from three fields, which were sampled the day previous to and about twelve hours after a rain of one and one-tenth inches. The sod land held about 80 per cent of the rain, while the cane and corn fields caught practically all that fell. The water retained by the sod land was all held in the upper few inches of the soil, while in the cane and corn fields it penetrated more deeply into the soil. The whole of the first foot received water, and there is some evidence of water reaching the second foot during even so short an interval and with so small an amount. There is an indication of loss from the third and fourth foot-sections in the cornfield. This may indicate what is said sometimes to take place after a rain—that the water just below moves upward to the soil moistened by the recent rain. Frequently indications of this kind have been found, and, when there is sufficient water below, there may be some upward movement caused by a change in the temperature at the surface. We have, however, attributed these slight changes to nonuniformity of the soil or to experimental error, the scope of either of which is sufficient to cover almost any such difference found.

In Table 11 are given the data obtained from sampling two fields at different times during the season of 1912. The lowest line of figures gives the amount of rainfall in inches during the period just preceding the date of sampling. It will be noted from the table that the sod land was very dry below the second foot at the time of the first sampling. The third foot shows an increase in the water content April 29 and the fourth foot at the following sampling. The following two periods, May 25 and June 10, show a slight increase in moisture in the fifth foot. After this date the soil water is used by the grass and the soil is not again moistened below the first foot. The moisture reached the lower depths in the sod land only during the period of frequent rains.

The data given in the second portion of the table were obtained from a field adjacent to the sod land, which was in oats 1911 and sown to cane 1912. This field was kept clean cultivated until July 3, when it was sown to cane. It will be noted from this portion of the table that the maximum amount of water shown on any sampling date in the upper six feet of soil was on May 11. It was not evenly distributed on that date. The upper three feet contained more than they could hold for any considerable length of time. After May 11 the weather was dry, and only light showers fell until after the cane was seeded (July 3) and began using water. The water content of the soil shows a loss during this period. There is a gradual downward movement of water in the soil in this field from April 22 to June 29, at which date the lower depths contain more water than at any other sampling date during the season. The increase in moisture content in the lower depths at this date was due to the excess water from above moving downward and not to additional water from rains. After July 26, the crop not only uses the rainfall that comes, but uses the water that was stored in the soil during the early part of the season. The samplings are too infrequent to show from what portions of the soil it was first used. The table also shows that the cane crop used water from the soil at a depth of six feet.

TABLE 11.—*Effect of surface condition and amount of water in soil, on penetration, 1912.*

PER CENT MOISTURE IN THE SOIL.

Depth	Prairie sod										
	April 18	April 22	April 29	May 11	May 25	June 10	June 29	July 25	July 26	Aug. 22	Sept. 12
Feet											
1	16.6	22.5	22.4	20.8	13.3	9.6	5.1	6.8	12.1	5.5	9.9
2	12.5	15.0	21.6	17.8	14.9	9.1	5.4	6.3	6.3	5.2	5.6
2	8.3	8.4	11.8	15.6	13.8	11.1	6.0	6.0	6.4	5.6	5.5
4	7.7	7.9	8.2	9.5	10.3	9.6	6.1	6.7	7.5	5.8	5.7
5	8.0	8.2	9.0	8.8	9.1	9.4	5.9	7.2	8.1	6.0	6.0
6	8.1	9.1	8.8	7.9	8.0	8.7	5.6	6.8	8.0	5.9	6.4
Average	10.2	11.8	13.6	13.4	11.6	9.6	5.7	6.6	8.1	5.7	6.5
	Cane field										
1	19.2	23.6	25.8	24.4	21.5	17.9	15.8	14.8	20.4	9.2	9.5
2	13.8	15.2	17.5	20.4	18.8	17.3	14.0	15.5	16.3	8.9	8.4
3	11.2	11.5	12.1	18.7	16.9	15.9	15.1	13.9	14.9	9.6	8.1
4	10.9	10.7	11.2	12.3	14.9	14.6	13.3	13.6	13.5	9.5	8.3
5	9.9	9.6	10.3	10.3	11.4	12.1	12.8	12.6	12.0	9.6	9.2
6	9.9	9.9	10.3	10.1	10.3	11.7	13.0	12.0	11.3	10.3	9.8
Average	12.5	13.4	14.5	16.0	15.6	14.9	14.0	13.7	14.7	9.5	8.9
Inches of rain since preceding sampling		1.11	1.66	1.78	0.13	0.41	0.25	2.27	1.10	1.93	1.25

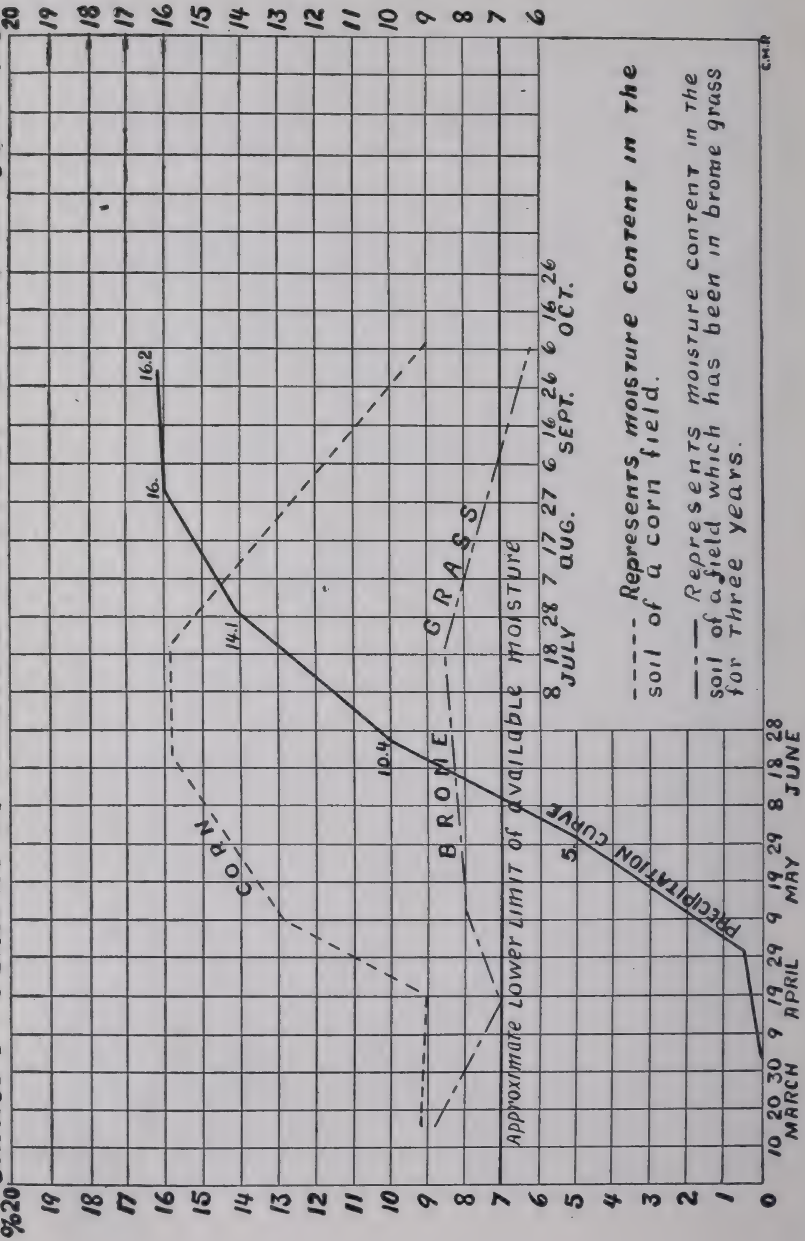

CHART V PERCENT OF MOISTURE IN FIRST 6 FEET OF SOIL 1908

The curves shown in Chart V represent the moisture content in a brome grass field and also a field which was in corn in 1908. The brome grass was seeded in 1905. The moisture content is practically the same in the two fields in the spring. The cultivated field soon begins to increase in moisture content, reaching its maximum in June and holding it until late in July. At the time that the crop required most water the soil was filled to almost full carrying capacity. The brome grass field did not accumulate much water tho the rainfall was high, as shown by the heavy, solid line. These curves illustrate again the effect of tillage and plant growth on the amount of water accumulated in the soil. The fields are adjacent, and the difference shown is doubtless due to the tillage in the cornfield, which retained more of the rainfall, and the growth of brome grass which used the water as fast as it came. The corn was young and not using much water until in July. As compared with the grass field there were far fewer plants on a given area to use water.

EFFECT OF CULTIVATION.

Cultivation is the one practical means for storing moisture in the soil on any considerable acreage. Our experience shows that summer tillage is the most efficient method for storing water which we have followed. A number of other methods, however, have been studied, to determine their effect. In the tables relative to the effect of the condition of the surface, it was shown that a cultivated surface would catch more water than a smooth surface. The difference that will be shown between the amount of water held by a cultivated surface and that held by a smooth surface is greater during heavy rains than during light rains. It has also been found that plowed ground or listed ground usually catches more water from any certain rain than does a surface which has been disked. Cultivation not only puts the surface in shape to catch the rain but is the means by which the moisture is saved after it has gotten into the soil. By cultivation, weeds are killed and thereby prevented from using the water, and the surface is loosened, forming a soil mulch which reduces evaporation from the surface.

In the following tables are given data obtained relative to the effect of cultivation. Space allows for only a small portion of the data which we have on any of these subjects. The results, however, are usually quite similar and we have aimed to show only representative results. Many times the weather conditions are such that no great difference is shown between one method and another. In other cases a greater difference is found.

TABLE 12.—*Effect of disking after the binder on soil moisture.*

PER CENT MOISTURE IN THE SOIL.

	Depth	1907		1908				
		July 11	Aug. 24	April 23	May 11	June 13	July 2	July 10
Soil disked	*Feet*							
	1	12.2	9.0	12.3	18.4	22.2	18.4	16.3
	2	6.3	7.8	9.0	10.3	12.0	16.6	15.0
	3	6.6	7.2	8.8	9.7	11.7	13.2	13.7
	Average....	8.4	8.0	10.0	12.8	15.3	16.1	15.0
Not disked	1	11.6	6.1	11.7	17.0	20.7	17.1	13.9
	2	6.2	5.6	9.6	9.6	12.9	16.8	13.9
	3	6.2	6.1	10.3	10.3	9.2	12.4	12.2
	Average....	8.0	5.9	10.2	12.3	14.3	15.4	13.3

	Depth	1911					1912	
		Aug. 5	Aug. 21	Sept. 11	Sept. 23	Oct. 20	July 31	Sept. 18
Soil disked	*Feet*							
	1	10.1	10.3	11.3	12.1	16.1	7.9	14.2
	2	7.0	7.0	7.2	8.9	13.1	7.0	7.7
	3	7.1	6.7	6.9	7.3	7.2	7.2	7.7
	Average....	8.1	8.0	8.5	9.4	12.1	7.4	9.9
Not disked	1	10.5	8.7	6.4	7.1	15.5	9.2	13.9
	2	6.8	6.9	6.7	6.8	6.6	6.9	7.9
	3	6.9	6.9	6.7	6.9	7.2	7.3	7.9
	Average....	8.1	7.5	6.6	6.9	9.8	7.8	9.9

In Table 12 are given the results of four tests in disking small grain stubble after the binder. In 1907 we note that with the close of the test, August 24, there was 3 per cent more water in the first foot of soil which had been disked than where the soil was not disked. There is also an increase in the second foot. During this interval of time more than two inches of water fell, 30 per cent of which was saved by the disking, while in the other field not only was all this water lost but the soil was actually drier at the end than at the beginning of the test. The weeds, which are usually found on the small grain fields, had taken this water. This difference in moisture content was sufficient to put the portion which had been disked in fair condition to plow, while the other was entirely too dry.

In 1908 the work was done on a piece of land which had been in small grain the previous year, and was being summer tilled. A portion of the field was left in the spring without disking; the other portion of the field received two diskings before the close of the test, when the field was plowed. It will be noted that there was very little difference in the moisture content of these two tracts up to June 13. After this date the difference becomes greater. During the interval when this work was being done, a total of ten inches of water fell. This was sufficient to replace in the soil not disked any water which may have been lost from the surface or used by weeds. The sampling was done only to three feet, and it may have been that more difference would have been seen below this depth. In 1911 no difference in the moisture content was found in the first foot between disked land and land not disked. But where the soil had been disked there was an accumulation of more than one inch of water in the second foot, while no water had penetrated into the second foot where the soil was not disked. During this interval a total of 5.5 inches of rain fell. In 1912 in the field recorded in Table 12 no benefit was found from disking.

TABLE 13.—*Effect of disking after the binder on soil moisture, 1912.*

PER CENT MOISTURE IN THE SOIL.

	Depth	July 27	July 29	August 2	August 5	August 12
	Inches					
Disked	1-6	18.9	13.3	21.8	17.0	13.6
	7-12	7.6	6.8	7.8	8.4	9.6
	24	6.0	5.4	5.5	5.6	5.1
	36	7.2	7.5	7.1	6.6	7.0
Not disked	1-6	17.2	9.6	19.0	13.6	6.2
	7-12	6.8	6.6	6.8	6.4	5.7
	24	5.8	5.7	5.8	5.8	5.6
	36	6.3	6.2	6.1	6.8	6.2

In Table 13 are given data obtained from disking winter wheat stubble after the binder. In this case there is shown a benefit of about 7 per cent in the first 6 inches and 4 per cent in the second 6 inches from disking. In the portion of the field that was disked most of the weeds were killed. There were considerable weeds on the portion not disked. These weeds doubtless used what moisture was available. The difference in the moisture content of these two plats was sufficient to make the plat which had been disked plow in good shape while the other was too dry to plow.

In summing up the data given in these two tables, it seems that moisture is conserved by disking following the binder if there is sufficient water in the soil after harvest to start weeds. In some cases we do not get a great deal of difference in the moisture content while in others we get a greater difference. But the disking will usually serve a twofold purpose. It will loosen the surface of the soil to catch and retain water and will kill most of the weeds. It is, however, frequently so dry after harvest that it is necessary to weight the disk in order to make it cut into the soil deeply enough to kill the weeds.

In Table 14 are given some data obtained from three plats of soil in 1912. On one of these plats the soil was kept thoroly stirred with a disk and any weeds which escaped the disk were cut with a hoe. On another plat the surface was not cultivated, but the weeds were kept cut with a hoe. The third plat was not cultivated and the weeds were allowed to grow. At the close of the test it is shown that there was very little more water in the upper three feet of soil where it had been disked than where it had not been disked. There is a difference, however, in the moisture content of the 4th, 5th, and 6th feet, which indicates that more water was caught and retained on the surface which was disked than on the smooth surface. The soil on which weeds had been growing was dry all the way down except the first foot. The moisture shown in the first foot was acquired from a rain just previous to the last sampling.

Table 15 gives the results from a test made to determine the relative effectiveness of plowing and disking to store water. The disking was done August 22 and the plowing August 25 and 29. The plowing was done to a depth of five to six inches. The disk was not weighted, but was set as deep as it would cut. Most of the weeds were killed by the disking and the surface soil was all stirred. During the interval in which the test was conducted, a total of 2.25 inches of rain fell. It will be noted from the table that during the period the plowed soil retained enough water to increase the moisture content of the second foot. In the disked soil there is no increase in moisture content in the second foot. The greater loss of water shown in the first foot in the disked soil than is shown in the first foot in the plowed land may be due to some weeds having escaped the disk and then having used the water, or it may be due to the water being held closer to the surface in the disked soil and exposed to greater evaporation.

TABLE 14.—*Effect of cultivation and weeds on soil moisture, 1912.*

PER CENT MOISTURE IN THE SOIL.

	Depth	April 15	May 3	May 25	July 4
Soil disked	*Feet*				
	1	16.6	19.4	16.0	14.9
	2	15.9	18.4	16.6	13.5
	3	10.3	17.7	16.2	13.4
	4	......	......	......	13.0
	5	......	......	......	13.9
	6	......	......	......	13.6
	Average....	14.3	18.5	16.3	13.7
Soil not cultivated. Weeds cut with hoe.	1	16.0	17.1	14.3	13.1
	2	14.7	16.6	15.2	12.4
	3	9.9	14.9	14.5	13.1
	4	......	......	......	12.0
	5	......	......	......	9.5
	6	......	......	......	8.6
	Average....	13.5	16.2	14.7	11.5
Soil not cultivated. Weeds growing.	1	16.0	16.5	9.1	14.5
	2	14.5	15.0	8.3	6.5
	3	9.0	9.6	9.0	6.5
	4	......	......	......	6.1
	5	......	......	......	7.0
	6	......	......	......	6.9
	Average....	13.2	13.7	8.8	7.9

TABLE 15.—*Plowing versus disking, effect on soil moisture, 1907.*

PER CENT MOISTURE IN THE SOIL.

	Depth	Sept. 2	Sept. 4	Sept. 6	Sept. 10	Oct. 9
Soil plowed	*Feet*					
	1	17.6	17.1	15.8	15.9	14.8
	2	5.9	8.4	9.1	10.4	11.1
	3	5.3	6.1	6.9	6.9	8.3
	Average......	9.6	10.5	10.6	11.1	11.4
Soil disked	1	17.0	17.4	15.5	14.8	12.8
	2	5.9	8.9	6.7	7.7	6.8
	3	6.2	6.2	6.3	6.7	5.8
	Average......	9.7	10.8	9.5	9.7	8.5

TABLE 16.—*Effect of cultivation on soil moisture, 1910.*

PER CENT MOISTURE IN THE SOIL.

Depth	Disking			Plowing		
	May 22	May 28	Gain	May 22	May 28	Gain
Feet						
1	13.1	16.8	3.7	14.8	17.1	2.3
2	10.7	10.9	....	11.3	14.7	3.4
3	8.9	8.8	....	9.6	9.3	. ..
Average .	10.9	12.2	....	11.9	13.7	....

In Table 16 are given additional data to show the difference between a plowed surface and a disked surface in retaining water from a rain.* During the interval a rain of .85 inch came. Practically all of the water which fell was retained in the plowed land. The disked soil held 65 per cent of the rain, all of which was held in the first foot of soil. In the plowed soil the moisture content of the second foot was increased.

All of the considerable number of tests that have been made during the past several years show an advantage of plowing over disking to store water. In many cases the difference is very small and depends largely on the weather conditions and the weeds that escape the disk. If the weather continues dry during a test of this kind or if the disking kills the weeds as thoroly as the plowing, little difference will be found. If the disking, however, does not kill all the weeds the difference will be greater, depending upon the amount of water used by the weeds. Where heavy rains come during the test, the advantage of plowing over disking will be greater. The plowing puts the soil in better shape than does the disk to catch the heavy rains.

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* This rain is shown in the records as 1.44 inches. This amount fell in North Platte, as reported by the U. S. Weather Station. The precipitation tables are made from the Weather Bureau records, because they are kept at the Substation only during the growing season.

TABLE 17.—*Effect of cultivation and growing weeds on soil moisture, 1908.*

PER CENT MOISTURE IN THE SOIL.

	Depth	May 2	May 22	June 11	June 29	July 31	Aug. 18	Oct. 29
Not cultivated. Weeds cut with a hoe.	*Feet*							
	1	13.6	17.3	17.6	17.4	14.6	13.1	16.6
	2	14.8	18.4	16.7	17.5	16.7	13.7	16.5
	3	13.4	16.9	15.0	17.0	15.8	14.2	15.0
	4	13.4	15.3	13.7	16.9	15.8	14.7	15.5
	5	12.4	12.8	12.7	16.2	14.6	14.0	14.1
	6	12.0	12.0	13.2	15.0	14.1	13.6	13.1
	Average . . .	13.3	15.5	14.8	16.7	15.3	13.9	15.1
Thoro cultivation.	1	17.8	20.8	20.0	20.4	18.7	16.6	21.3
	2	15.7	20.0	18.5	20.9	18.1	16.4	17.9
	3	14.1	17.0	16.7	18.0	17.0	15.3	15.0
	4	13.8	15.1	15.6	17.5	16.5	15.3	14.4
	5	13.1	12.8	15.0	16.0	15.2	15.2	13.7
	6	11.7	11.7	12.8	14.2	13.7	13.8	13.9
	Average . . .	14.4	16.2	16.4	17.8	16.5	15.4	16.0
Not cultivated. Weeds allowed to grow.	1	15.3	17.1	. . . .	14.6	12.0	9.0	16.0
	2	14.9	18.3	. . . .	11.0	9.3	8.1	14.0
	3	13.8	16.9	. . . .	11.9	9.1	7.6	8.1
	4	13.8	12.2	. . . .	9.6	9.0	8.5	7.9
	5	12.9	10.8	. . . .	10.0	7.8	8.3	7.6
	6	12.6	11.7	. . . .	11.9	9.7	9.2	8.3
	Average . . .	13.9	14.5	. . . .	11.5	9.5	8.5	10.3

In Table 17 are given the data obtained in 1908 from sampling three plats, each of which received different treatment. The plat labeled "Thoro cultivation" received what was considered ideal cultivation. The surface was kept well mulched and free of weeds. The plat labeled "Not cultivated. Weeds cut with a hoe," was not cultivated during the entire season. The weeds were cut with a hoe kept sharp so to disturb the surface as little as possible. A few weeds started on this plat, and used some moisture. The aim, however, was to cut them soon after starting, to prevent their use of water. Early in August the plat was neglected for a few days and the weeds made a considerable growth.

The third plat was harrowed about the middle of April. After that date no further work was done, and weeds were allowed to grow. The weeds were cut with a mower in August. The idea in this test was to check the effect of the neglect of cultivation with the effect of growing weeds. It is seen from the table that each of the plats contained nearly the same amount of water at the beginning of the test. No great variation is seen until June 29. It is noticed that the difference in water content between the thoroly tilled plat and the weedy plat is much greater than the difference between the thoroly tilled plat and the plat not cultivated but kept free of weeds. There was several times as much water lost from the weedy plat as from the one where only cultivation was lacking.

It must be borne in mind that this work was started with a soil almost filled with water, and carried on during a season of heavy rainfall. There was no prolonged or extremely dry spell of weather this season. The results apply to the loss of water after it has been gotten into the soil, and show that on this type of soil under a normal rate of evaporation growing weeds cause a much greater loss of water from the soil than surface evaporation. We cannot say what the results would have been if we had started with a soil filled with water and had run the test thru a very dry season. It is probable tho that the loss from an uncultivated surface would be much greater. The results given in Table 14 show that during a less favorable season and starting with a soil comparatively dry below the second foot, there is much less water retained from the rains where the surface is not cultivated than is retained by the cultivated surface, which further proves that from the viewpoint of storing water a cultivated surface is essential.

ARTIFICIAL MULCHES.

It is a rather common practice to use artificial mulches among shrubs, small fruit, and in some cases vegetables. The Station has done some work to determine the value of artificial mulches from the viewpoint of catching and holding the water that falls. These mulches are usually composed of old hay, straw, or manure. From the viewpoint of retaining water, they are most efficient and have a practical application. Wherever it is desired to grow shrubs, ornamentals, or small fruit, the mulch can be used for retaining water. Against its efficiency in holding water the opinion is sometimes advanced that it forms a harboring place for injurious insects. We have no data on the latter point. In the following tables the effect of the mulch on the water content of the soil is shown.

We are offering two tables on the effect of mulch. A number of tests have been made along this line, all of which have given practically the same results, and have shown that an artificial mulch of hay or straw several inches thick, if kept intact, is more efficient than a soil mulch in retaining water. It is obvious that water would find less resistance in entering the hay mulch than it would in a soil mulch. The hay mulch is also more efficient as shown by Table 18 in checking loss from evaporation.

TABLE 18.—*Effect of mulching on soil moisture, 1912.*

PER CENT MOISTURE IN THE SOIL.

	Depth	August 28	September 5	November 15
Hay mulch	*Feet*			
	1	25.7	18.4	16.5
	2	22.9	16.9	25.0
	3	20.5	16.7	15.9
	4	14.4	15.9	14.5
	5	14.1	15.0	14.7
	6	14.9	15.3	15.5
	Average	18.8	16.4	17.0
No mulch	1	25.0	14.8	11.1
	2	22.3	15.5	9.4
	3	19.8	15.3	10.1
	4	15.2	15.3	13.3
	5	13.7	14.5	13.5
	6	13.6	14.3	12.8
	Average	18.3	15.0	11.7
Soil mulch	1	24.8	16.1	14.3
	2	22.3	16.1	14.5
	3	19.5	16.0	13.8
	4	15.5	16.8	14.0
	5	12.6	16.5	14.4
	6	13.5	15.5	14.6
	Average	18.0	16.2	14.3

The data given in Table 18 were obtained from a small tract of land which was watered August 27, 1912. It was intended that enough water would be added to saturate the soil to a depth of six feet. The sampling August 28 showed that the upper three feet of soil contained more water than could be retained against gravity, while the second three feet were low in their water content. A second sampling was made September 5 which showed a quite normal or equal distribution of the water. Immediately after sampling on the 28th of August, one portion of the tract was covered with several inches of hay. A second portion was not mulched until the surface became dry enough to work, when it was stirred to a depth of about one and one-half inches with a hoe. The third portion was left untreated. After putting on the hay, no further attention was given this mulch. The plat where the soil was stirred to retain a mulch was kept free of weeds and the surface stirred occasionally. The portion not worked at all soon became weedy. Tho only a few weeks of growing season remained, a considerable growth of redroot, foxtail, and other grasses was produced. Just how much of the water lost from the plat not mulched was used by the weeds cannot be stated. Judging from the amount of growth, the major portion of the loss must have been from this cause.

The table shows an average difference in the amount of water held until the close of the experiment of a little more than one per cent in favor of the hay mulch over the soil mulch, showing that a mulch of straw or hay is more effective in reducing surface evaporation than one made by stirring the soil.

TABLE 19.—*Effect of mulching on soil moisture, 1911.*

PER CENT MOISTURE IN THE SOIL.

	Depth *Feet*	July 31	August 11	Gain
Not mulched	1	9.9	15.8	5.9
	2	7.1	6.9	....
	3	7.2	7.2	....
Hay mulch	1	10.8	15.3	4.5
	2	7.8	13.5	5.7
	3	7.9	7.8	....

In Table 19 are given the data obtained from two samplings on adjacent plats of ground, one of which was covered with hay as a mulch and the other left bare. During the interval between the two samplings a total of 1.65 inches of rain fell. The plat left not covered retained from this about .9 inch or 55 per cent of the total rain, all of which was retained in the first foot of soil. The plat covered with a hay mulch retained 1.57 inches or 95 per cent of the total rainfall. More than one-half of the amount held penetrated into the second foot. The hay mulch would reduce the loss from evaporation to a minimum while the exposed surface of the plat not mulched would permit a more rapid loss of water by evaporation.

LOSS OF WATER FROM THE SOIL.

There are three ways by which water may be lost after it has been gotten into the soil: First, by escape downward by percolation; second, by evaporation from the surface; third, by transpiration, or by being used by plants.

Of the first-named means of loss little need be said. It is seldom that we get enough water into the soil at this Station to allow percolation beyond the reach of the plant. Percolation does not take place until a soil is filled beyond its carrying capacity. This point is seldom reached, and, if reached, we cannot control percolation.

The second means of escape, that is, by evaporation from the surface, is to a certain extent under the control of the farmer. There will always be some loss, but it can be reduced to a minimum. The water that evaporates from the surface reaches the surface much the same as oil from the bowl of the lamp reaches the flame. The water passes from one soil particle to another until it reaches the surface and is lost by evaporation. This upward movement is much more rapid when the soils are wet and is retarded as they dry out. If the surface of the soil is cultivated it becomes loose and dry. Either condition tends to retard the further movement of water to the surface. Water moves very slowly thru a loose or dry soil. In this section a rain is usually followed by a hot sun and wind. These cause a more rapid loss of water from the surface than can be supplied by capillarity from adjoining soil particles. The result is that the soil surface soon dries. This is in itself a check to surface evaporation. The water from below moves slowly thru the dry surface. If the rain was of sufficient amount to make the surface smooth and connect with the under moisture, it should be stirred as soon as practical. In order to reduce evaporation from the surface to a minimum, it is essential to have on the surface not only a dry soil, but a loose soil. Cultivation will stir the surface soil, cause it to dry out more quickly, and leave the soil grains not so closely in contact. The fewer the points of contact between the small particles of soil and the drier they become, the more effective is the mulch in reducing evaporation. Another reason for cultivation soon after a rain, especially where a field is bare, is that a smooth soil blows much more quickly than a rough soil. This, of course, applies to the soils that are light enough to blow and in regions of frequent high winds.

On this type of soil we feel that two to three inches is sufficiently deep to make an effective mulch. Where the mulch is too shallow, there will be enough circulation of air thru the mulch to cause considerable loss. On this soil almost any implement that stirs the surface can be used if it does not pulverize the soil too finely. Where the surface has become so dry that the drag-harrow pulverizes, we prefer the disk. On still lighter soils the disk might pulverize too much and make some other implement preferable. The objections to a real fine or dust mulch are that it will blow and that it offers too great resistance to the penetration of water.

The third means of escape of water from the soil, that of being drawn out by growing vegetation, is much more effective on this type of soil than surface evaporation (see Tables 14 and 17). Considering only the moisture content of the soil, the water used by any plant is lost. From the point of view of the farmer, only the water used by weeds is lost. This is, of course, a real loss, since the weeds have little value. The water that is taken up by the roots of the crops, passed thru the plant, and then exhaled by the leaves, has served its purpose in plant growth. It is for that purpose that we strive to store the moisture in the soil.

DEPTH TO WHICH CROPS HAVE USED MOISTURE.

The depth to which a crop will use moisture depends upon the root development of the crop, the length of its growing season, its normal development, and the type of soil on which it is being grown.

Some crops make more root development than others and naturally send their roots deeper into the soil to obtain water and plant food. An extreme example of deep feeding is seen in alfalfa. Other crops feed to a lesser depth. The length of the growing season also affects the depth to which water is used. A perennial crop, such as grass, will dry the soil to a considerably greater depth in a series of years than it will in one year. It may be that there is some continued growth of the roots, and that they keep growing so long as they can find water; or the drying of the lower soil may be due to the water being brought to the roots by capillary action during the greatly extended time. Winter wheat, due to its longer growing season, develops a deeper root system than does spring wheat, and consequently uses the water from a lower depth than does spring wheat.

During a very unfavorable season a crop may become so injured that it will not make normal development and consequently does not use the water to as great depth as it would had it developed normally. Indications of this were observed in a number of plats in 1911. The crops were so damaged by the hot winds that they died while available water was within their reach, had they made normal devolopment. The water was not available in considerable amount but could have been used under normal conditions. The demand for water, under such extreme conditions, was greater than could be supplied from a soil so nearly dry and to a plant in a weakened condition.

The type of soil is an important factor in determining the depth to which crops will feed. On a loose or a sandy soil that offers but little resistance to the penetration of the roots, a plant will send its roots to a greater depth than on a heavier soil that offers more resistance. A layer of gumbo or hardpan underlying the surface soil at no great depth will prove more or less impervious to plant roots and cause the crop to feed in the soil above. Shale or rock has the same effect but it is more marked. It is a matter of common observation that during dry seasons the crop will suffer first on those spots in the field where an impervious stratum of some kind comes nearest the surface.

In the following tables are given data to indicate the depth to which some of the various crops send their roots and use the moisture. The per cent of water in the soil at seeding time and at harvest is shown. Summer tilled land was used in every test. This, in every test, gave available water in every foot-section to a depth greater than the plant would use it. By comparing the water content of the soil at seeding and harvest times we can see to what depth water was used:

TABLE 20.—*Depths to which crops have used moisture. Summer tilled land.*

PER CENT MOISTURE IN THE SOIL.

Crop	Depth	1907		1908		1909		1910		1911		1912		Average per cent moisture in soil at harvest time
		Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	
	Ft													
Oats	1	14.7	10.0	19.1	8.3	18.6	8.3	14.2	8.7	12.2	6.0	16.5	11.2	8.8
	2	14.2	8.6	16.1	8.6	16.2	8.0	17.0	8.8	12.2	6.9	6.7	7.7	8.1
	3	15.9	8.2	14.6	8.7	15.0	7.5	16.8	8.5	10.1	8.1	16.7	7.8	8.1
	4	....	8.8	14.2	9.3	15.1	8.1	16.0	9.5	12.3	10.8	12.6	8.6	9.2
	5	....	10.3	16.9	15.4	17.8	10.8	17.2	15.2	13.7	12.7	14.4	11.9	12.7
	6	....	10.7	16.3	14.9	16.6	14.2	18.4	15.0	13.8	11.4	13.3	12.9	13.2
Spring wheat	1	15.7	7.8	15.9	10.0	19.8	11.1	16.7	7.6	12.4	10.5	18.9	6.9	9.0
	2	16.9	8.2	15.7	8.7	16.0	9.7	16.0	9.5	12.0	7.2	17.6	6.8	8.4
	3	15.9	7.9	15.4	8.2	15.4	8.5	15.1	7.1	11.3	7.4	14.7	6.6	7.6
	4	....	8.6	14.9	9.0	16.0	9.0	14.7	8.1	12.0	8.6	13.8	8.2	8.6
	5	....	12.6	18.9	13.2	19.5	14.3	17.9	7.6	15.5	12.4	15.8	13.4	12.3
	6	....	13.9	18.0	14.3	17.8	14.9	18.7	14.4	14.6	13.3	15.3	12.8	13.9
Barley	1	16.6	9.6	17.2	11.6	18.1	10.8	14.8	14.4	11.6	6.6	17.7	6.6	9.9
	2	16.9	11.5	15.4	10.1	16.5	10.2	15.2	9.1	11.8	6.7	15.2	6.8	9.2
	3	15.3	10.2	14.1	9.9	15.4	8.9	13.9	8.3	11.0	8.9	13.8	7.3	8.9
	4	....	12.3	15.5	11.0	15.4	8.3	17.4	8.5	12.3	10.9	12.9	8.9	10.0
	5	....	14.9	18.8	15.7	18.8	12.7	10.2	14.5	14.7	14.7	15.5	14.5	14.5
	6	....	17.4	18.5	15.6	18.5	13.7	18.2	15.5	14.6	13.7	14.6	13.2	14.8

TABLE 21.—*Depths to which crops have used moisture. Summer tilled land.*

PER CENT MOISTURE IN THE SOIL.

Crop	Depth	1907		1908		1909		1910		1911		1912		Average per cent moisture in soil at harvest time
		Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	Seeding	Harvest	
	Ft													
Corn	1	18.9	11.1	15.3	7.5	17.5	10.1	18.1	16.2	20.1	12.4	18.3	15.9	12.2
	2	16.8	9.0	15.7	9.2	15.9	9.7	16.9	10.1	17.4	14.0	16.1	9.6	10.3
	3	15.0	9.2	14.3	9.1	14.7	10.0	15.4	10.2	14.3	13.8	15.2	10.3	10.4
	4	....	....	14.4	9.9	14.7	13.1	14.2	12.8	13.6	16.1	14.9	10.7	12.5
	5	....	....	17.6	14.9	17.2	16.8	18.7	16.4	17.5	16.9	18.0	14.1	15.8
	6	....	....	17.2	15.0	15.7	16.1	17.2	15.5	16.5	12.6	17.1	13.3	14.5
Winter wheat	1	....	....	18.4	11.4	16.8	11.9	14.9	7.4	13.3	13.2	19.8	11.8	11.1
	2	....	....	17.0	18.2	17.0	13.9	15.0	7.1	12.8	6.7	17.0	6.2	10.4
	3	....	....	15.8	8.3	16.5	8.5	17.6	8.0	11.7	6.1	12.8	6.1	7.4
	4	....	....	15.0	7.3	14.6	7.8	14.7	7.8	9.8	7.0	11.5	7.1	7.4
	5	....	....	13.8	6.9	11.9	7.6	14.6	6.9	9.0	7.6	10.1	8.0	7.4
	6	....	....	14.6	6.9	10.3	8.1	14.5	8.8	10.0	7.8	9.1	7.5	7.8
	7	....	....	....	....	9.1	8.3	15.6	10.7	11.6	8.0	9.4	7.9	8.7
	8	....	....	....	....	8.7	8.6	14.9	12.0	12.6	9.8	8.6	8.2	9.6
	9	....	....	....	....	8.8	8.7	15.5	13.0	12.8	10.0	6.9	8.4	10.0
	10	....	....	....	....	9.0	9.1	13.3	12.6	14.4	12.6	8.9	8.4	10.7

It will be noted from Tables 20 and 21 that in most cases a rather distinct break is shown in the water content at harvest time at some depth. Take for example oats. There is in every case a more or less wide break in the amount of water at harvest time between the fourth and fifth foot-sections. In fact this is generally true of all spring small grain crops. The break appears in the record to be abrupt. This is not quite true in the field, but is due to the method of taking the samples. The samples are taken in foot-sections and the break appears to come abruptly between them. If the samples were taken in inch-sections a gradual lessening in water content would be found to extend thru several inches. This rather abrupt break in water content seems to indicate the feeding depth of the roots. A sufficient number of roots go down to this point to take out most of the available water. There are frequently indications of loss of water from the section just below the drier soil. A few roots may have entered this lower depth and used some water, or the loss may be due to some water having moved by capillary action into the feeding zone of the roots. The amount of this water used by the roots from the lower depths is very small.

It will be noted in the tables that the first foot and even the second foot sometimes show considerable water at harvest. This water has been retained from rains coming after the crop matured and was not left there by the growing crop. The soil sampling marked "harvest" has not in all cases been taken immediately after harvest but has been taken before any water had reached the lower depths. In some cases a rain would come before the crop was off the ground, but after it had matured. In the column showing average moisture content of each foot-section at harvest, the amount of water in the first and second foot cannot therefore be taken as the limit to which the moisture was reduced when the crop had matured. This is especially true of winter wheat and corn. These amounts were obtained by averaging the amount of water at harvest in that foot-section for all the years.

From Table 20 it will be seen that oats, spring wheat, and barley feed to a depth of four feet or a little more. In some cases, as spring wheat in 1910, the available water has been used from the fifth foot. Taking the average, however, it shows the fourth foot dry and the fifth rather moist. Table 21 shows that corn does not take out as much water as do the small grain crops. This is probably due to the lesser number of plants on a given area and not to less ability of the plants to get water. Much the same results have been obtained from growing cane in rows. When the cane is drilled over all the ground and a greater number of plants must be supported, more of the water is used. The table shows that the corn feeds to a depth of at least four feet in this soil.

Winter wheat feeds deeper than corn or spring grain. It uses water from the sixth and the seventh foot. The difficulty in determining this point has been to get enough water in the soil at those depths so that the break in moisture content would show plainly. Many times there has been no available water in those sections even tho the field had been summer tilled. The evidence is that the roots penetrate to six or seven feet when there is available moisture. This is in accord with work done by the Wyoming Station and reported in an unnumbered pamphlet. A winter wheat plant was dug out and showed roots about six feet long.

EFFECT OF WEEDS.

As much water is required to grow a pound of dry matter in weeds* as is required to produce the same amount of dry matter in some of the farm crops. From the standpoint of the farmer who is farming under a limited rainfall, weeds are his worst enemies. Any water used by weeds is lost to the crop. It is hardly practicable to keep all weeds down, but the crop is usually cut short to the extent that it has been robbed of the water by weeds.

In the following tables we give data showing the effect of weeds on soil moisture. Weeds have the additional harmful effect of using available plant food, and, if allowed to use all the available water, leave the soil in such a dry condition that extra labor is required to get it into a good state of tilth.

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* Bul. No. 284, Bureau of Plant Industry, U. S. Dept. of Agr., by Briggs and Shantz.

TABLE 22.—*Effect of weeds on soil moisture, 1907.*

PER CENT MOISTURE IN THE SOIL.

	Depth	June 15	July 3	August 23	September 21
Where weeds were growing	*Feet*				
	1	16.9	11.9	8.7	9.5
	2	17.9	15.0	11.9	8.3
	3	16.6	14.9	12.7	8.0
	Average	17.1	13.9	11.1	8.6
No weeds	1	19.2	18.7	17.9	17.2
	2	19.1	17.0	17.7	16.3
	3	15.7	16.5	15.7	15.9
	Average	18.0	17.4	17.1	16.5

TABLE 23.—*Effect of weeds on soil moisture, 1908.*

PER CENT MOISTURE IN THE SOIL.

	Depth	May 22	June 29	July 31	August 18	October 29
Where weeds were growing	*Feet*					
	1	17.1	14.6	12.0	9.0	16.0
	2	18.3	11.0	9.3	8.1	14.0
	3	16.9	11.9	9.1	7.6	8.1
	4	11.2	9.6	9.0	8.5	7.9
	5	10.8	10.0	7.8	8.3	7.6
	6	11.7	11.9	9.7	9.2	8.3
	Average....	14.3	11.5	9.5	8.5	10.3
Weeds kept down	1	20.8	20.4	18.7	16.6	21.3
	2	20.0	20.9	18.1	16.4	17.9
	3	17.0	18.0	17.0	15.3	15.0
	4	15.1	17.5	16.5	15.3	14.4
	5	12.8	16.0	15.2	15.2	13.7
	6	11.7	14.2	13.7	13.8	13.9
	Average......	16.2	17.8	16.5	15.4	16.0

The plats from which the data given in Table 22 were obtained were treated alike until the first of June. At this date weeds were starting on both plats. They were allowed to grow on one plat, while the other one was cultivated and kept clean. More than three and one-half inches of water were lost from the upper three feet of soil where weeds were grown as compared with that kept clean. The soil was as dry as it would have been had it produced a crop. Cases similar to this are sometimes seen on farms where a tract is being summer tilled. The land is kept clean and water stored during a portion of the season. Then other work becomes urgent and the summer tilling is neglected. The weeds come on, using a part or all of the accumulated water, and the previous labor is largely lost.

The work shown in Table 23 is a continuation of that shown in Table 22 for 1907, on the effect of weeds. The same plats were used. There is a difference of almost two per cent of water at the first sampling. The plat that is kept cultivated does not accumulate any additional water during the season, as it is already filled with water. Instead of being summer tilled it should have been cropped. The plat that was allowed to become weedy lost moisture thruout the season, and was as dry at the time of small grain harvest as it would have been if it had been cropped. The plat that was kept clean contained more than five inches more water than the plat which grew the weeds.

TABLE 24.—*Effect of weeds on soil moisture, 1911.*

PER CENT MOISTURE IN THE SOIL.

Depth	Weedy	No weeds
Feet		
1	8.7	14.7
2	8.5	10.1
3	7.0	7.2
Average	8.1	10.7

The data given in Table 24 were obtained from a field which was being plowed May 20, 1911. It was noticed that where weeds were growing the soil was very dry and turned over lumpy and hard. Where there were no weeds, the soil was in good condition to plow and work down for a seed bed. Samples were obtained and the difference in the moisture content ascertained. The weeds were mainly Russian thistles and were small, averaging only two to three inches high. Their growth, however, had consumed over an inch of water, mainly from the first foot of soil. Had the land been worked and these weeds killed early in the season, this water would have been saved for the use of the crop and less labor required to prepare a good seed bed. Similar conditions are sometimes seen during dry seasons in fields which are being listed to corn. Where the weeds have been killed by a previous disking or other cultivation, the soil is in much better condition to list than where the weeds are growing. In seasons of more rainfall, the difference is less evident because frequent rains supply the water used by the weeds from the soil near the surface.

TABLE 25.—*Effect of weeds on soil moisture, 1912.*

PER CENT MOISTURE IN THE SOIL.

	Depth	April 15	July 4	November 5
Where weeds were allowed to grow	*Feet*			
	1	16.0	14.5	12.6
	2	14.5	6.5	9.5
	3	9.0	6.5	7.3
	4	....	6.1	6.1
	5	....	7.0	6.6
	6	....	6.9	6.8
	Average	13.2	7.9	8.2
Where weeds were kept down	1	16.0	13.1	14.3
	2	14.7	12.4	14.5
	3	9.9	13.1	13.8
	4	....	10.0	14.0
	5	....	13.5	14.4
	6	....	8.6	14.6
	Average	13.5	11.8	14.3

The data given in Table 25 were obtained from a test made where a small tract of land which had been fall plowed was allowed to become weedy. Another portion was kept cultivated. The plat where the weeds were kept down contained almost six inches more water at the close of the test than the weedy plat.

TABLE 26.—*Effect of weeds on soil moisture.*

PER CENT OF WATER IN THE SOIL, JUNE 23, 1913.

Depth	Soil free from weeds	Weeds growing	Loss by weeds
Inches			
1-6	20.6	8.8	11.8
7-12	18.4	8.7	9.7
13-18	17.0	9.1	7.9
19-24	11.4	9.1	2.3
25-30	8.5	8.2	....
31-36	8.4	8.0	....

The data given in Table 26 were obtained from two plats which were being summer tilled during the summer of 1913. The one kept free of weeds is worked according to the usual method of clean fallow. The other is plowed after the weeds start in order to save labor in the summer tilling process. Both plats grew a crop of winter wheat in 1912 and at harvest time contained practically the same amount of water. It will be noted that where weeds were growing practically no moisture had been accumulated in the first three feet. Where the weeds were kept down, moisture was accumulated to a depth of two feet. By keeping the weeds down, between two and one-half and three inches of water have been saved in the upper two feet of soil.

Growth of weeds on weedy fallow referred to in Table 26.

The data given in Table 27 were obtained from an experiment on disking grain stubble after harvest. A portion of the field was disked with a weighted disk. A portion of the field where weeds were growing was chosen for the work before disking. The disk killed most of the weeds. The balance were killed with a hoe. The work was of short duration, due to the fact that the field was plowed soon after the last sampling date. About two inches of rain fell after the disking was done and before the final sampling. It will be noted from the table that the weeds used this water. None of it get into the soil as deep as the second six inches. The soil was devoid of available water at the last sampling. Where the weeds were killed, a little more than one-half of the rain which fell was saved. The second six inches was moistened, and the soil was in good condition to plow. We attribute this difference more to the killing of the weeds than to the fact that the surface soil was disked. However, it was the disking that killed the weeds.

TABLE 27.—*Effect of weeds on soil moisture, 1912.*

PER CENT MOISTURE IN THE SOIL

	Depth	July 27	July 29	Aug. 2	Aug. 5	Aug. 12
Weeds killed with disk	*Inches*					
	1-6	21.2	14.6	21.6	16.5	12.0
	7-12	9.4	9.8	9.6	11.4	13.0
	24	5.4	5.3	5.4	5.7	6.5
	36	5.4	5.7	5.3	5.9	5.7
	Average......	8.7	7.7	8.8	8.5	8.2
Weeds growing	1-6	17.2	9.6	19.0	13.6	6.2
	7-12	6.8	6.6	6.8	6.4	5.7
	24	5.8	5.7	5.8	5.8	5.6
	36	6.3	6.2	6.1	6.8	6.2
	Average.....	8.0	6.7	7.9	7.5	5.9

In Chart VI is graphically shown the water content, by foot sections to six feet, in the soils of three plats receiving different treatment. The data are shown in Table 17. The solid line represents the water content of a plat receiving the best tillage we could give it. The broken line represents the water content in a plat not cultivated but the weeds kept down with a hoe. The line designated by crosses represents the water content in a plat where weeds were allowed to grow. This chart shows that growing weeds were a much greater factor than lack of cultivation in losing water from this soil when previously filled with water. After the weeds had been killed by frost so that they were no longer using so much water, rains partially filled the first two feet of soil. The difference at the last sampling is therefore not so great as earlier in the season.

Chart VII shows graphically the use of water from the soil by a corn crop. For explanation of chart, see that given for Chart III. This plat was summer tilled in 1907 and cropped to

CHART VI.—EFFECT OF WEEDS AND CULTIVATION ON THE MOISTURE CONTENT OF THE SOIL.

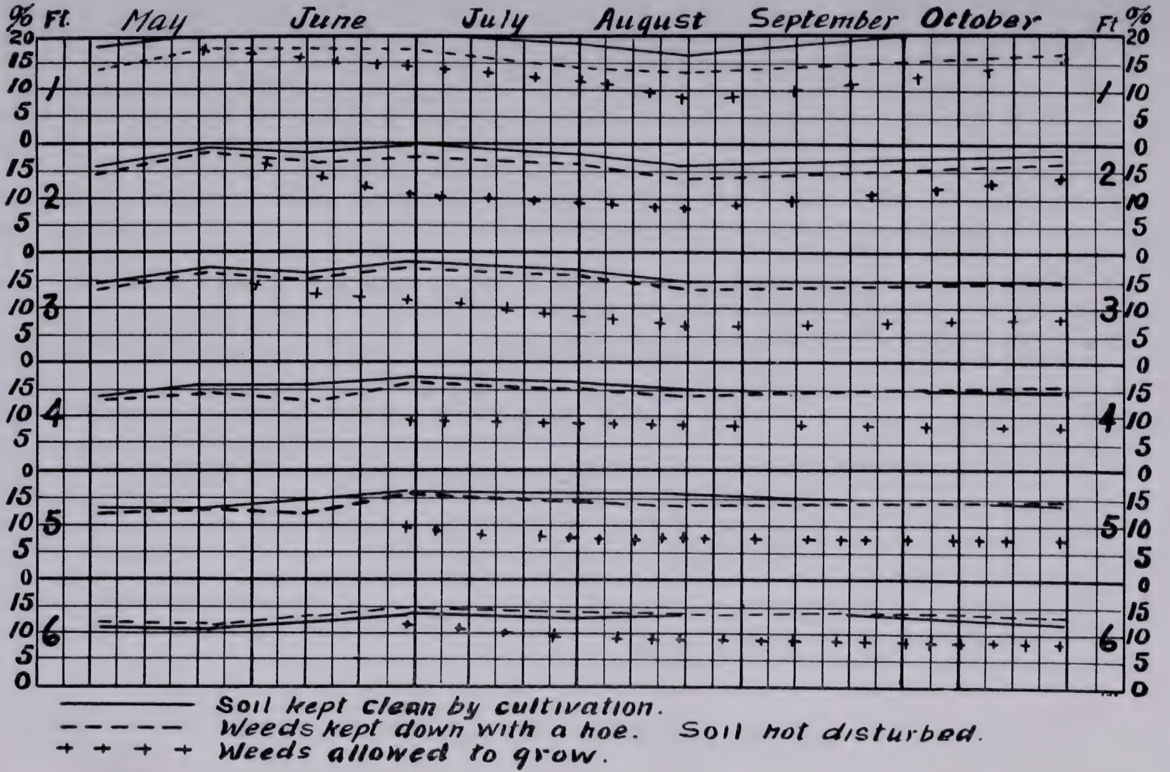
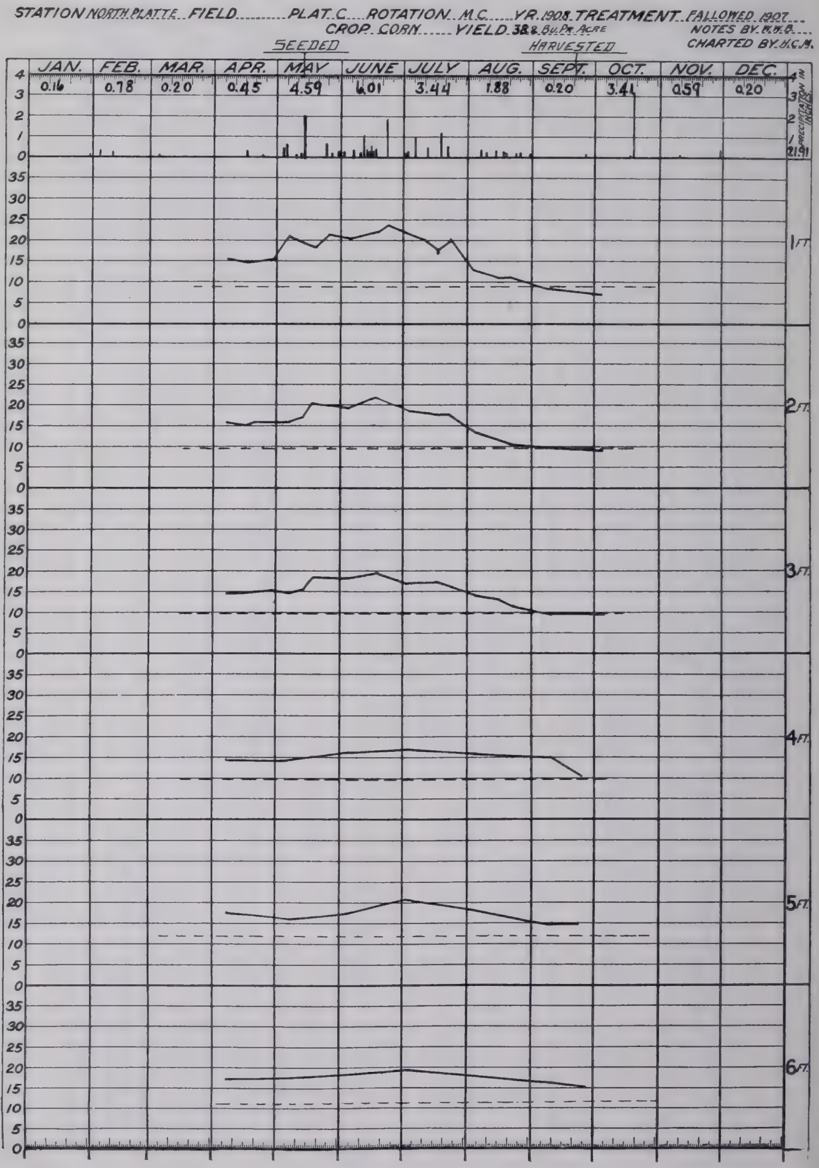


CHART VII.—USE OF AVAILABLE WATER BY A CORN CROP.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

corn in 1908. At the sampling about June 20, the moisture content of the first three feet is above carrying capacity. This sampling was done so soon after a rain that the moisture had not had time to move downward. The first sampling in July shows that this moisture had moved into the lower depths, as indicated by the abrupt rise in the curves in the fifth and sixth foot-sections. After July 20 the crop not only uses the light rains that come but uses the available water from the first four feet of soil. The use of the water from the first three feet of soil is rather gradual and simultaneous. From the fourth foot it is abrupt. The first four feet are dried to about 10 per cent. The fifth and sixth feet contain 15 per cent at harvest, showing that the roots feed to at least four feet.

The data in Table 28 were obtained from frequent sampling made on a plat summer tilled 1912 and growing spring wheat 1913. It was hoped to show more clearly how the moisture is used from the soil. At the first sampling the first and second feet are taken in foot-sections. Thereafter they are divided into six-inch sections. The table shows the soil practically filled with water at the first sampling. Very little water is used the first month. Rains occasionally replenish the water near the surface. On June 23 the third foot was practically dry and on July 8 the fourth foot was dry. Some water is lost from the fifth and sixth foot-sections but the abrupt break in water content comes between the fourth and fifth foot-sections.

In Chart VIII is shown the use of the soil water by spring wheat. In each case the crop was on summer tilled land. Only the water available to the crop, or that above 8 per cent, is represented. The depth is indicated on the left of the chart. The dates shown indicate when the samples were taken. Each small vertical space represents 5 per cent of available water.

The chart shows that under the favorable rainfall conditions the crop did not reduce the water content of the soil until after the June samples were taken. There was enough rainfall to replace any water that was used. In 1909 the July sampling showed the water used from the first and second foot had been replaced with water from a recent rain.

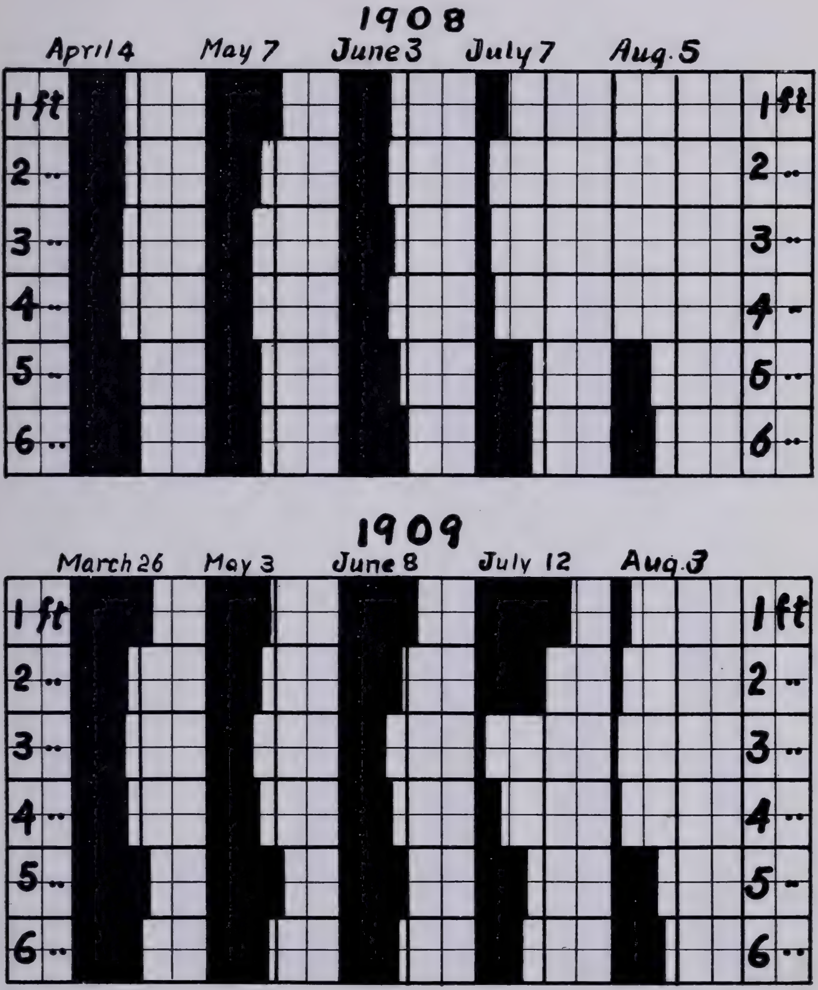
In 1908 the crop was seeded April 4 and harvested August 3. The yield was 40.5 bushels an acre. In 1909 the seeding was done April 12. The crop was harvested July 29 and yielded eighteen bushels an acre. The crop this year was injured by a freeze in April. The chart further proves that spring wheat feeds to a depth of four feet. In each case it used practically all the avail-

TABLE 28.—*Use of water from soil by spring wheat, 1913.*

PER CENT MOISTURE IN THE SOIL.

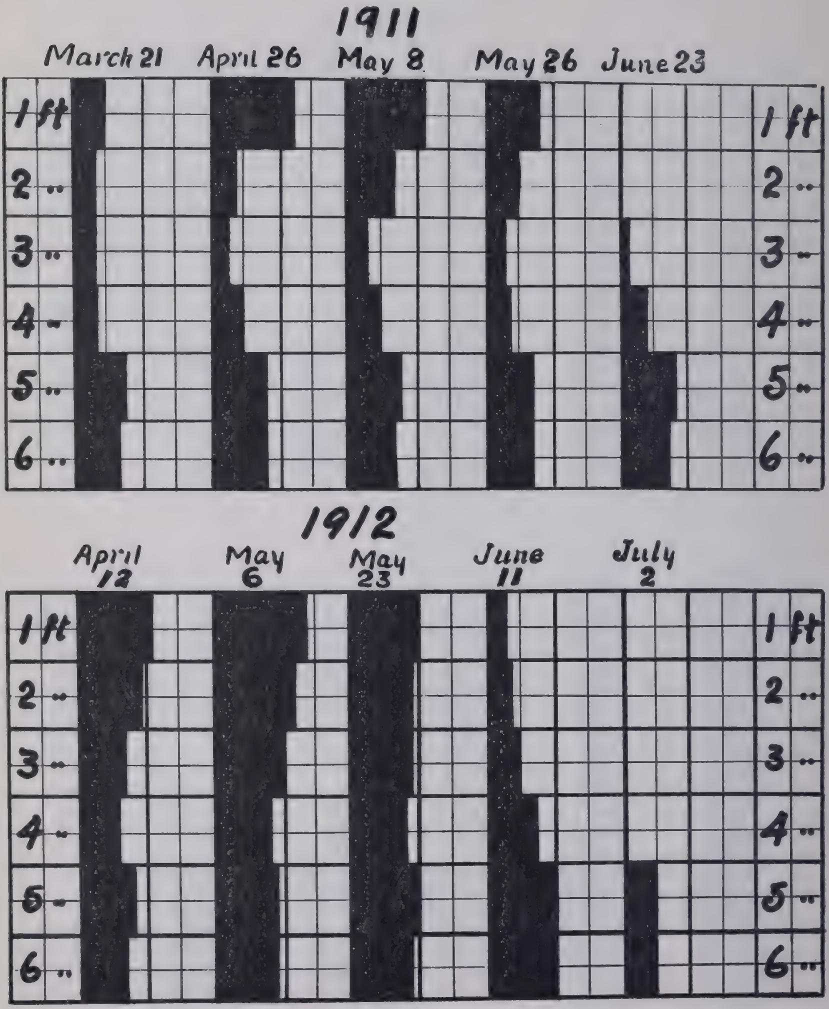
Depth	April 28	May 26	May 30	May 31	June 2	June 5	June 7	June 10	June 13	June 18	June 20	June 23	June 30	July 8
Inches														
1-6	....	16.5	9.5	16.4	13.5	14.4	17.3	13.1	16.1	9.6	13.7	9.6	6.1	6.2
7-12	17.7	14.7	12.0	12.7	10.3	11.4	12.2	10.0	9.8	8.6	8.5	9.1	6.9	7.4
13-18	....	15.3	13.3	13.3	11.7	11.8	12.8	10.2	11.0	8.9	8.7	8.8	7.2	7.5
19-24	15.7	15.3	13.8	13.9	12.7	13.0	13.3	11.1	10.5	9.7	8.3	8.9	7.8	7.3
36	15.6	....		....	14.2	....	....	....	....	....	....	9.2	....	7.7
48	15.6	....	....	....	15.4	....	....	....	....	....	....	12.9	....	8.6
60	18.7	....	....	....	18.6	....	....	....	....	....	....	18.0	....	14.9
72	16.9		....	....	17.0		....	....	....	....	....	15.6	....	14.6

CHART VIII.—USE OF AVAILABLE WATER FROM THE SOIL BY SPRING WHEAT.



From top to bottom each division of the chart represents one foot-section of soil. From left to right each division of the chart represents 5 per cent available moisture.

CHART IX.--USE OF AVAILABLE WATER FROM THE SOIL BY SPRING WHEAT.



From top to bottom each division of the chart represents one foot-section of soil. From left to right each division of the chart represents 5 per cent available moisture.

able water to that depth and did not use any appreciable amount from below four feet.

Chart IX shows again the use of the available water by the crop. In each case the land was summer tilled the previous year, and the crop used was spring wheat. In 1911 the first sampling does not show the usual amount of available water. As previously shown, summer tilling in 1910 did not accumulate much water. June 23, the last sampling, shows some available water in the third and fourth feet. At this date the growth was still sustaining itself, and showed evidence of making a crop. Grasshoppers, however, destroyed the crop soon after this date and the sampling was neglected. A sampling made early in September showed no available water in the fourth foot.

The 1912 chart shows an increase of available water during April and May. It also shows the use of the water from the soil earlier in the season than was shown for either year given in Chart VIII. A comparison of the distribution of the rainfall for these years will account for this. The crop was seeded April 12, harvested July 25, and yielded 10.5 bushels an acre.

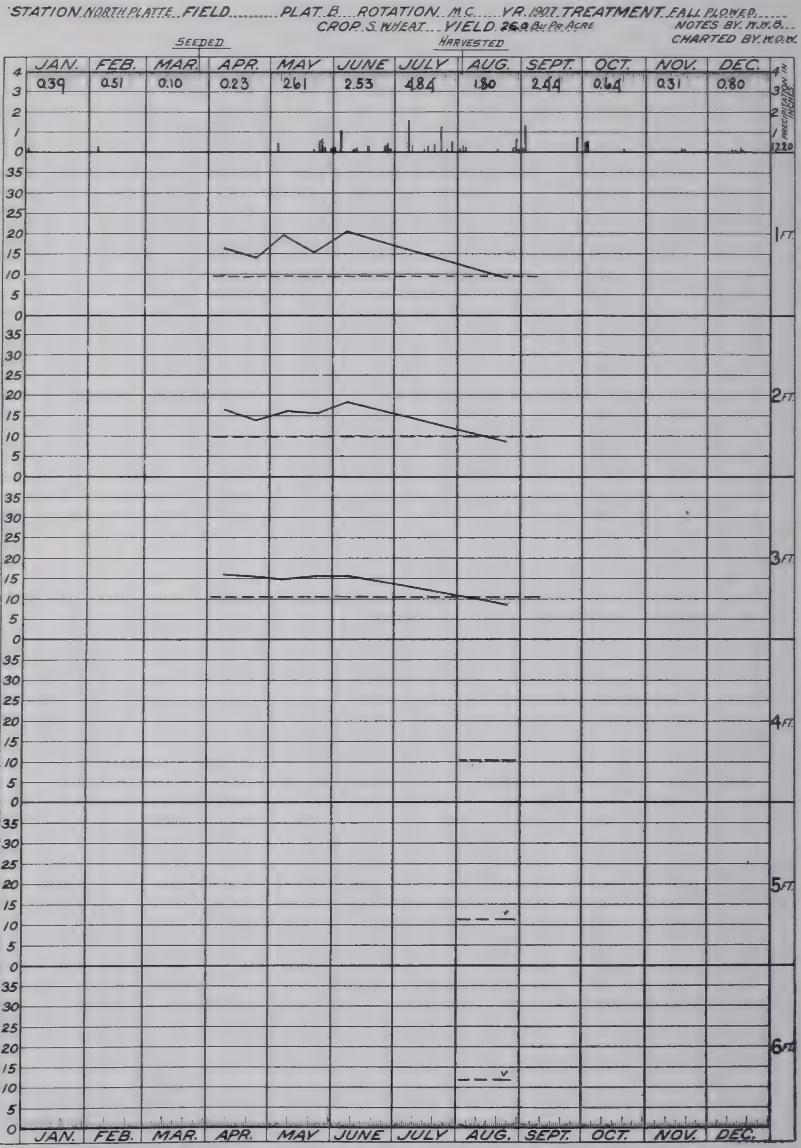
Charts X to XV are offered to show the effect on the moisture content of the soil of continuous cropping to small grain.

The same general explanation that was given for Chart III will answer for Charts X to XV inclusive. The curves shown in these charts represent the moisture content for each foot-section of soil to a depth of six feet. All rains of one-tenth inch or more are shown in the division for precipitation. The seeding and harvest dates are marked on each chart, except 1911, when there was no harvest. The yields are shown for each year. Each chart represents the moisture content of the same plat for the year shown thru the six consecutive years. This plat has grown the same crop, spring wheat, and received much the same tillage each year. It is fall plowed and harrowed as soon as practical after harvest.

In the spring of 1907 the soil was practically filled with water to a depth of three feet. This was as deep as the sampling was done. The first sampling after harvest shows the soil dry to four feet.

The first sampling in 1908, as shown in Chart XI, shows available water in the first two feet of soil. This had been retained from rain or snow during the winter. The first and second feet were completely filled by the heavy rains in May. June shows a very heavy rainfall and some water passed into the third foot. Below this there was practically no change in

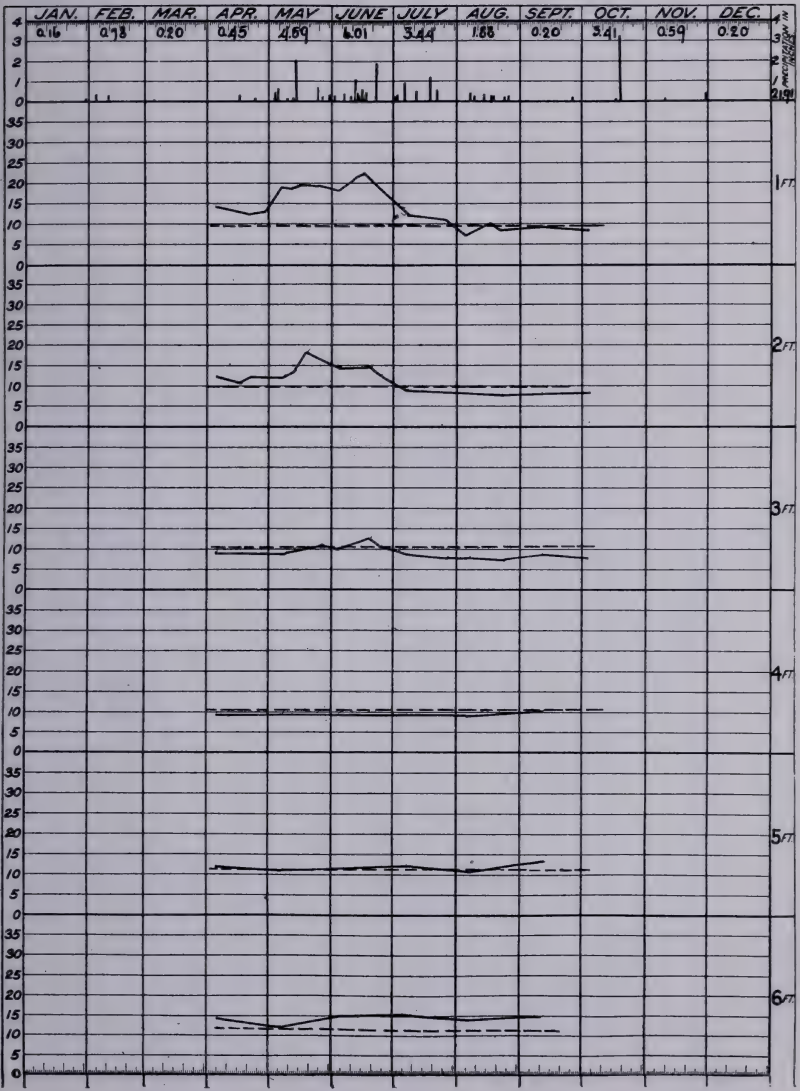
CHART X.—MOISTURE CONTENT OF PLAT CONTINUOUSLY CROPPED TO SPRING WHEAT.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

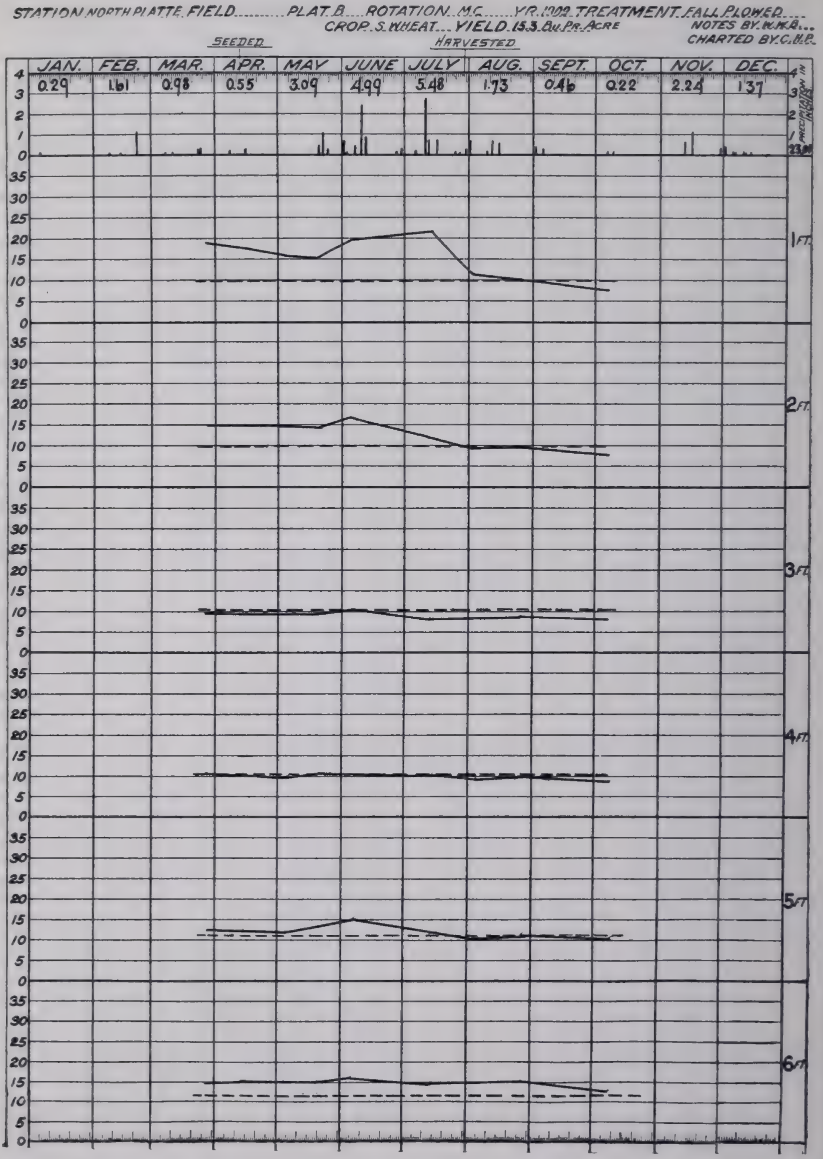
CHART XI.—MOISTURE CONTENT OF PLAT CONTINUOUSLY CROPPED TO SPRING WHEAT.

STATION NORTH PLATTE FIELD.......... PLAT B.... ROTATION M.C...... YR. 1908 TREATMENT FALL PLOWED.....
CROP S. WHEAT.... YIELD 27.3 Bu. Pr. Acre
NOTES BY W.W.B...
CHARTED BY N.O.W.



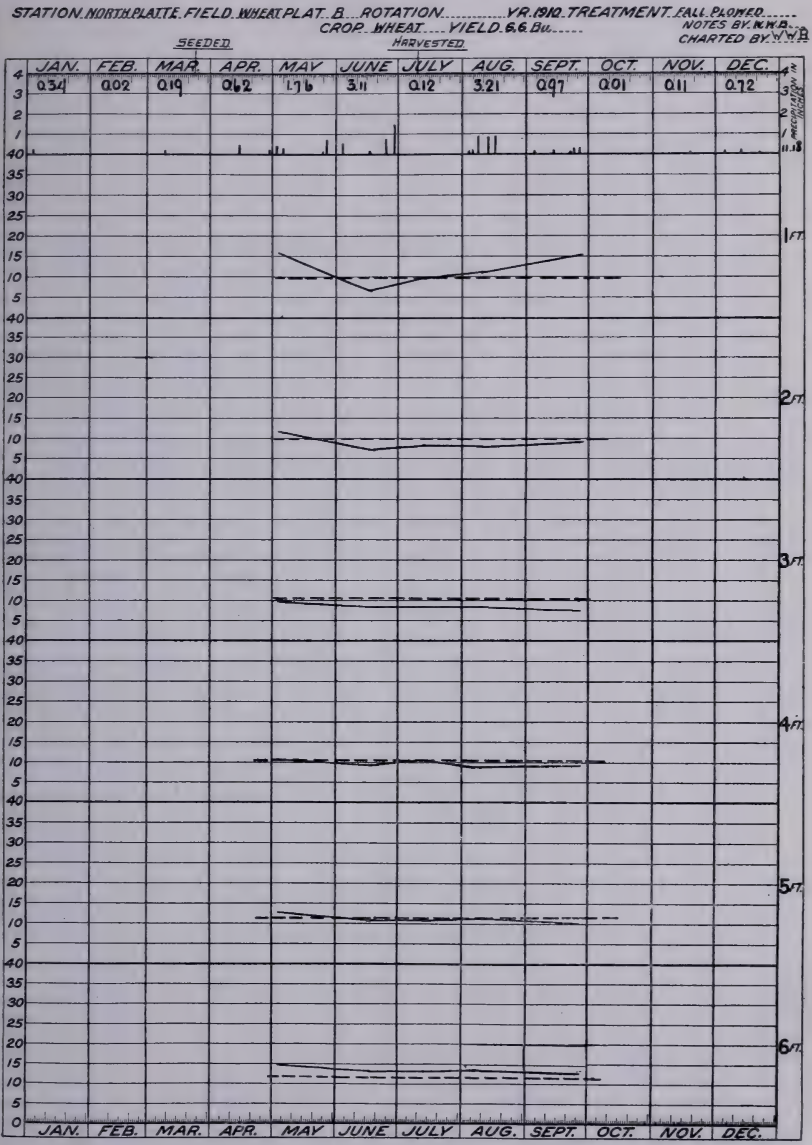
Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

CHART XII.—MOISTURE CONTENT OF PLAT CONTINUOUSLY CROPPED TO SPRING WHEAT.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

CHART XIII.—MOISTURE CONTENT OF PLAT CONTINUOUSLY CROPPED TO SPRING WHEAT.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

water content. At harvest all available water within reach of the crop had been used. Chart XII shows available water in the first two feet of soil. This was held from the very heavy rain in October, 1908, shown in Chart XI, and from the snow shown in February, 1909. During the entire season, tho there were several heavy rains, no water reached the third foot. The chart indicates a change in the water content of the fifth foot. This is doubtless due to error for there is no such change indicated in the third and fourth feet.

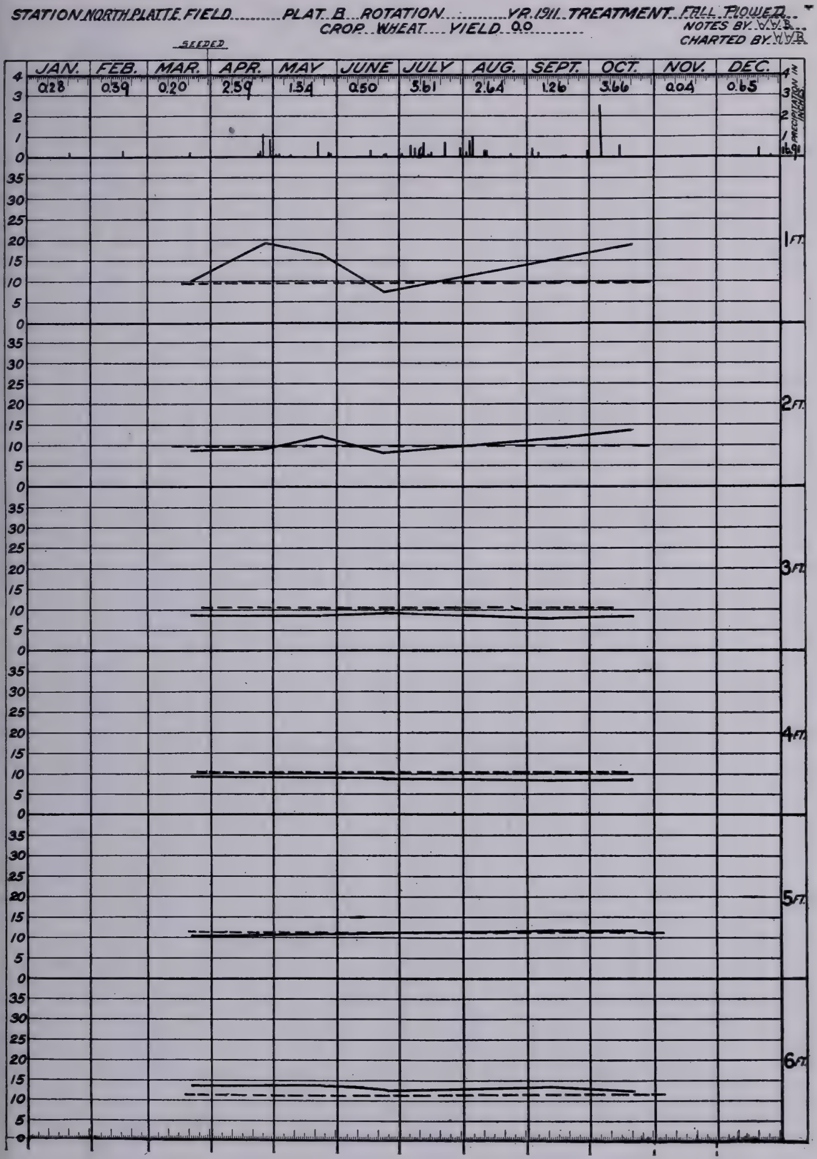
Chart XIII shows at the first sampling an accumulation of water in the first foot of soil and a very little available water in the second foot. The third foot and below remain dry thruout the season. The second foot becomes dry during May and remains dry thruout the remainder of the season. It will be noted from this chart that during the latter part of May all available water was exhausted from the soil. From this time until harvest the crop was entirely dependent on the rain. Just enough rain came to pull the crop thru. The crop did not ripen naturally, but simply dried. This is shown by the harvest date which is very early as compared with the preceding years shown.

Chart XIV shows that there was no available water in the soil at seeding time. This made the crop entirely dependent on the seasonal rainfall. The rainfall was deficient. During the early part of the season, while the crop was small and using very little water, only a small amount of water accumulated in the second foot. The latter part of May the crop began to suffer. By June 4 all growth had ceased, and by June 15 the crop was dead. With the exception of the slight increase in water content of the second foot in May, it remained dry all the season until the heavy rain in October. The second foot was practically dry from the last of July, 1909, until the first of October, 1911.

Chart XV shows available water in the first two feet of soil in February, 1912. In May the moisture has increased, filling the first three feet and passing into the fourth, fifth, and sixth. The rainfall of May and June was almost as low as for the same months in 1911. The crop had the reserve water in the soil to draw upon, however, and made a yield of 11.2 bushels an acre. The chart shows how rapid the crop will use water from the soil when it is forced to depend almost entirely on the water in the soil. Without the reserve in the soil the crop would have died of drouth in May or June.

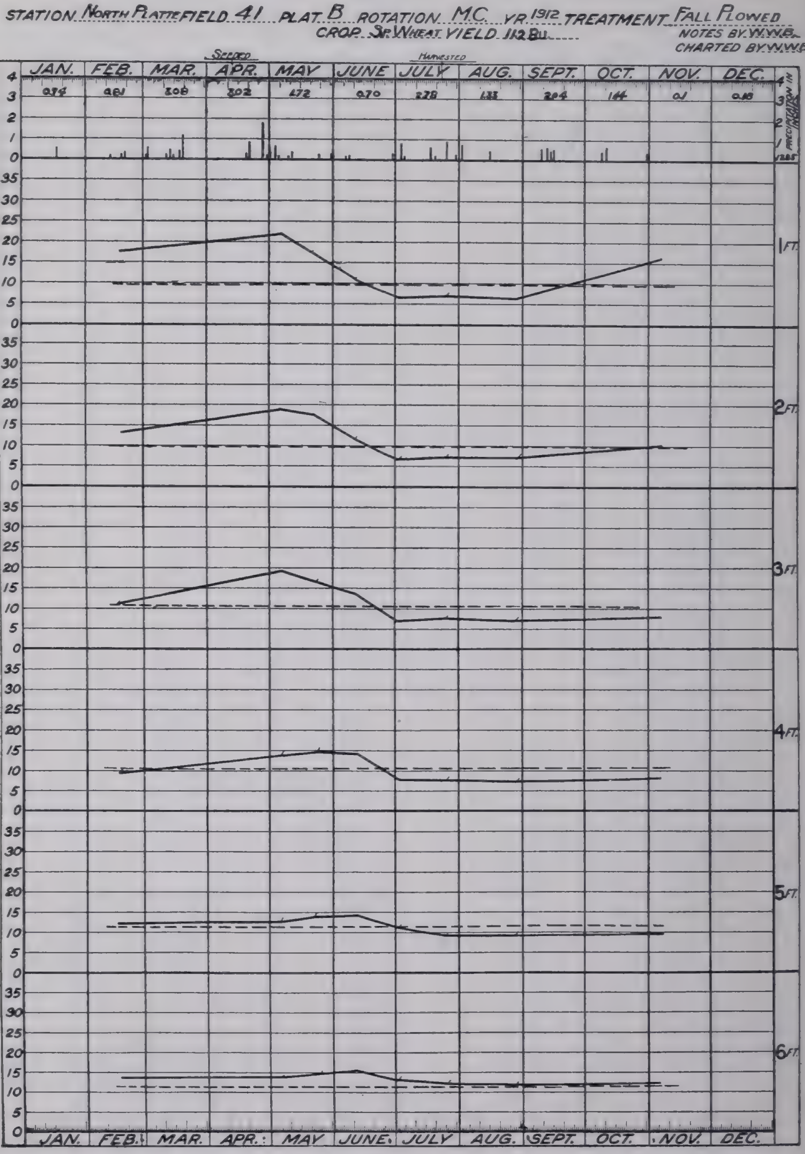
The heavy precipitation of March and April, 1912, supplied water to the third foot of soil for the first time since it became dry the latter part of June, 1908.

CHART XIV.—MOISTURE CONTENT OF PLAT CONTINUOUSLY CROPPED TO SPRING WHEAT.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

CHART XV.—MOISTURE CONTENT OF PLAT CONTINUOUSLY CROPPED TO SPRING WHEAT.



Irregular solid line represents the moisture content of that foot-section. Broken line represents the point at which crops wilt, as determined by Briggs and Shantz.

The fourth foot had been dry since harvest, 1907. This shows that it requires large quantities of water to wet the soil to a depth of four feet. It is seldom done on this type of soil and under our rainfall except by summer tillage or irrigation.

TABLE 29.—*Effect of capillarity on soil moisture.*
Alfalfa on bench land.

PER CENT WATER IN SOIL.

Depth	June 24, 1910	March 20, 1911	June 29, 1911	April 22, 1912	Nov. 14, 1912	April 2, 1913
Feet						
1	8.5	10.5	8.5	21.0	11.6	21.6
2	8.2	8.8	8.5	15.0	8.7	17.3
3	8.2	8.5	8.4	8.4	8.2	16.5
4	8.0	8.7	8.7	8.4	8.1	9.1
5	8.4	8.7	9.1	8.2	8.7	9.1
6	8.2	9.4	8.6	8.9	8.7	8.9
7	8.3	8.9	9.3	8.7	9.1	8.9
8	7.4	9.0	9.1	9.0	9.2	8.4
9	8.9	11.1	9.1	10.1	9.4	9.7
10	10.6	13.0	9.7	13.7	11.6	14.1
11	10.3	12.2	9.8	12.2	11.3	12.3
12	10.8	13.0	9.6	12.7	10.1	12.1
13	10.8	14.0	15.0	15.7	11.2	16.9
14	12.8	19.3	17.2	21.3	14.4	22.2
15	21.0	24.6	21.0	24.8	20.5	27.6

The data given in Table 29 were obtained from a field of alfalfa growing on the bench land. Sheet water is from 17 to 21 feet below the surface. There is a rise and fall in the level of the sheet water during the year, depending on the flow in the river two and one-half miles north.

The table shows that during the winter months when the alfalfa is not using the water, there is an increase in the moisture content of the soil from the sheet water to the ninth foot from the surface. The table shows a fluctuation in the water content of the first three feet of soil, due to water from rains or snow on the surface. Practically no change is found in the water content of the next five feet. No water has passed thru this to increase the content below. The lowest section obtained, the fifteenth foot, being closest to sheet water, is most nearly saturated. The amount of water in each section above this diminishes until we reach a point where capillary action is equalized by the force of gravity and the upward movement of water stops. During the summer the crop uses this water. The fifteenth foot is, however, close enough to the sheet water so that there is a constant supply rising within the soil zone occupied by the lower roots of the alfalfa. It should be remembered that this rise of water into the lower levels shown in Table 29 is due to the presence of sheet water only a few feet below, so that the upward rise of water in this soil does not in any way diminish the per cent of water in the soil immediately below it and that this action would cease very soon after the free water was exhausted.

The soil in this field has not been dried in any section as dry as the same section in the alfalfa field on the table-land. The plants seem to find it easier to raise the water from below than to take more from the soil in the intermediate sections. During the years 1910 and 1911 a field of alfalfa on the table-land died for lack of moisture. The alfalfa was seeded in 1902 and was well established in the soil. During the same years the alfalfa on the bench not only lived thru but produced almost normal crops of hay.

In Table 29 was shown the effect of capillarity when operating just above a constant supply of free water. Under these conditions the force was very active and within certain limits would be a great factor in crop production. In Table 30 are given data to show its effect when removed from a supply of free water. In this table the fourth foot of soil is shown to be practically dry from June, 1910, to July, 1911. The fifth foot contains about four per cent more water, and is only three or four per cent below saturation. We do not find, however, that any water is drawn from the fifth foot to replace that which had been used by the crop from the fourth foot. Even in a period of seventeen months the content of either foot remains very little changed. In fact we have abundant proof that capillary movement is feeble in soils that are dried any considerable extent below the saturation point. The evidence indicates that, in the main, the plant roots, to obtain water, extend themselves into the soil zone where available water is present, rather than depend upon the water being brought to them by capillarity.

TABLE 30.—*Effect of capillarity on soil moisture.*

Depth	1910					1911						
	May 3	June 17	July 19	August 15	Sept. 28	March 21	April 26	May 8	May 23	June 23	Sept. 11	Oct. 20
Feet												
1	16.7	7.9	7.6	12.7	16.3	10.4	21.6	16.8	20.6	17.1	16.6	19.5
2	16.0	8.5	9.5	7.8	9.4	9.0	9.5	13.8	13.1	14.3	15.1	17.5
3	15.1	8.1	7.1	7.8	8.0	8.8	8.0	7.6	8.8	7.8	12.6	14.5
4	14.7	9.7	8.1	8.8	9.6	9.9	10.1	9.6	9.7	10.3	9.6	10.1
5	17.9	15.6	14.0*	13.4	13.2	13.8	14.3	13.7	13.3	13.7	13.7	13.6
6	18.7	17.4	14.4	14.0	13.8	13.9	13.4	14.1	13.7	13.5	14.6	14.0

* Estimated.

TABLE 31.—*Water required to produce one pound of dry matter of various crops.*

Crop	Year	Average per cent water in upper 6 feet of soil		Per cent water used from soil	Water used from soil—tons per acre	Precipitation during growing season, inches	Total water available to crop from soil and precipitation—tons per acre	Dry matter produced, pounds per acre	Pounds of water required for one pound of dry matter
		Seeding	Harvest						
Spring wheat	1908	11.8	11.3	.5	52.2	12.8	1505.3	3980	756
	1909	13.6	13.1	.5	52.2	12.1	1422.5	3530	806
	1910	12.6	10.5	2.1	219.5	6.2	926.3	1350	1372
	1912	16.9	8.5	8.4	878.2	7.6	1740.0	2580	1345
Corn	1908	13.0	8.6	4.4	460.0	14.4	2090.8	4380	955
	1909	11.7	12.8	.9	....	14.2	1516.4	5000	606
	1910	13.9	11.1	2.8	262.7	5.4	898.6	2950	610
	1912	16.8	12.3	4.5	470.4	6.8	1240.6	5120	485
Cane	1908	15.4	7.9	7.5	784.1	6.6	1534.9	10600	290
	1909	14.3	7.3	7.0	731.8	8.1	1653.7	8740	378
	1910	13.3	7.3	6.0	627.2	2.9	952.3	7000	272
	1911	10.3	7.5	2.8	313.6	7.0	1106.4	2200	1000
	1912	13.9	8.9	5.0	522.7	7.2	1338.1	5640	475
Winter wheat	1908	16.2	8.2	7.0	731.8	13.6	2277.7	7260	627
	1909	12.1	10.3	1.8	313.6	15.8	2103.0	6768	621
	1910	15.0	10.0	5.0	971.2	10.9	2105.7	5436	775
	1911	11.4	8.4	3.0	418.2	7.7	1292.5	2448	1056
	1912	12.3	8.0	4.3	599.4	15.2	2319.7	2520	1841*

* There was a heavy run-off when the snow melted this spring, and this is charged to the crop.

WATER REQUIRED TO PRODUCE ONE POUND OF DRY MATTER OF VARIOUS CROPS.

In computing the amount of water required to produce a pound of dry matter, we have taken the water used from the upper six feet of soil for each crop except winter wheat. With winter wheat we used a greater depth in order to include its entire feeding range. The difference in water content of the soil at seeding and harvest dates is figured as the water used from the soil. The total rainfall from seeding date to harvest date is charged to the crop. The crop does not actually use all this water. Some of it is lost thru surface evaporation. Some is lost as run-off. Especially was this true in the case of winter wheat in 1912. When the heavy snows of that spring melted the soil was frozen below a depth of three inches. Not only did we lose this moisture as run-off but the snow melted so fast that in some cases it washed off the unfrozen soil.

The entire rainfall plus the water drawn from the soil is figured as total available water. Dividing the total number of pounds of water by the number of pounds of dry matter produced, we have the number of pounds of water to produce one pound of dry matter. This table is not offered for its technical value. The method of procedure was too crude to give it much value from that standpoint. We are using it to prove what observation has so often indicated, that during unfavorable seasons a given amount of water will not produce as large a crop as during favorable seasons. An inch of water in a favorable season goes much further than a like amount in an unfavorable season. The table shows that some years almost twice as much water is required to produce a pound of dry matter as is required in certain other years. The total rainfall alone is not sufficient to interpret results. The distribution of rainfall, evaporation, temperature, relative humidity, and wind velocity, all affect the efficiency of the rainfall in crop production. The rainfall of this section is seldom so low but that it would produce fair crops if properly distributed and accompanied by a favorable rate of evaporation. The high rate of evaporation and the hot winds resultant from drouthy conditions are frequently more disastrous than the drouth itself. In a few days these will injure a crop to the point where it can at best only partially recover, whereas under more favorable conditions it would have held on for a considerable length of time and perhaps have been saved by a rain. This is often shown by results obtained from protected areas.

The table also shows that a year which is favorable for small grain is not necessarily favorable for corn. An example of this is seen in 1908. The small grains did not use an excessive amount of water. Corn used more water than during any other year. In 1912 the small grains used a large amount of water and corn shows the best use of the available water of any year shown.

CLIMATIC CONDITIONS.

In order that the data offered in this bulletin may be more clearly understood, we are giving several tables to show the climatic conditions under which this work was done. Figure 2 and Table 32 give annual precipitations and show years of high and years of low rainfall. Other tables give the average daily temperature, wind velocity, and rate of evaporation from a free-water surface for certain months for the years 1908 to 1912. These averages show almost as wide variation as the rainfall. The averages are, however, not so important as the extremes. For example, in Table 37, June, 1911, shows an average wind velocity of 10.5 miles per hour. In that month the daily average for the four days, 12th to 15th, was about fifteen miles an hour. There were hours within these days when the wind velocity was much higher than others. It is the extreme conditions that are critical. Those four days would do much more damage to the crop than many days of less wind. The extreme wind velocity within these days was doubtless much more damaging than the average. Another example is in Table 36. The highest average monthly evaporation given is for June, 1911. The four days, 12th to 15th, which showed such a high wind velocity, also show a high evaporation. Such days as these are what we call extreme conditions. We will not attempt to give a discussion of the climatic conditions, but a study of the several tables offered will show more clearly why some of the results were obtained.

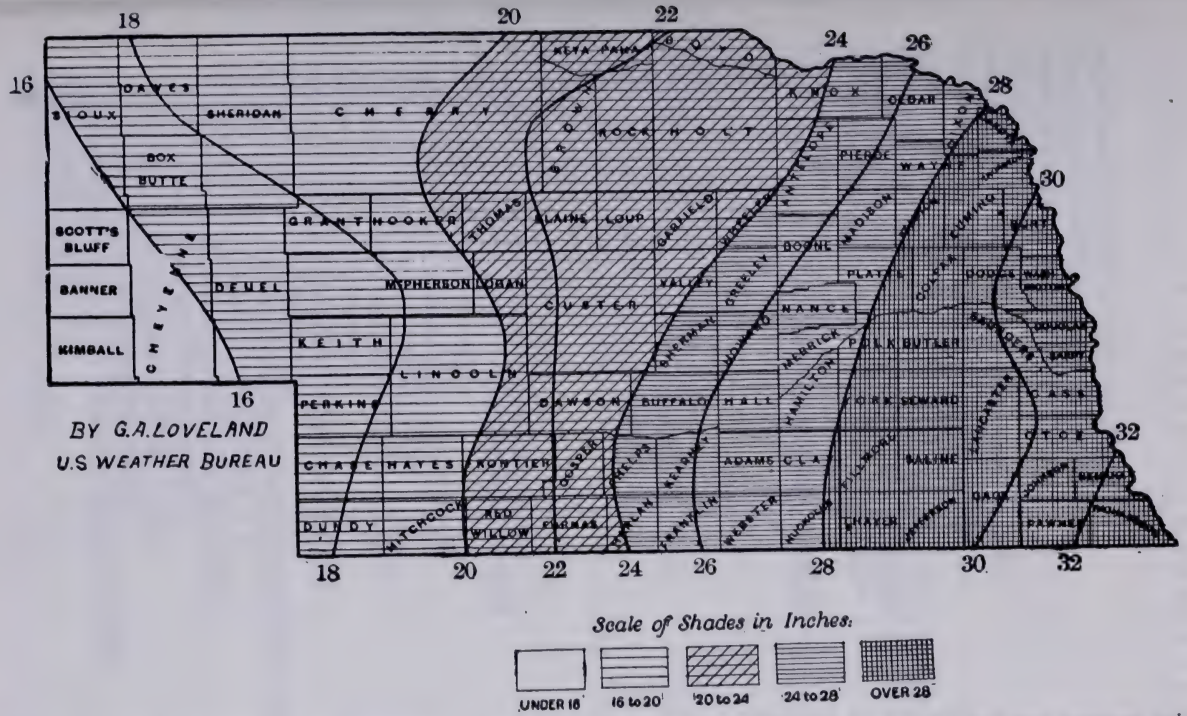


Fig. 1.—Normal precipitation in Nebraska. Map showing rain belts. Figures on margin indicate average rainfall within the region, according to United States Weather Bureau. Region between "18" and "20" has received an average of from 18 to 20 inches of rainfall annually from 1850 to 1912, according to the United States Weather Bureau record.

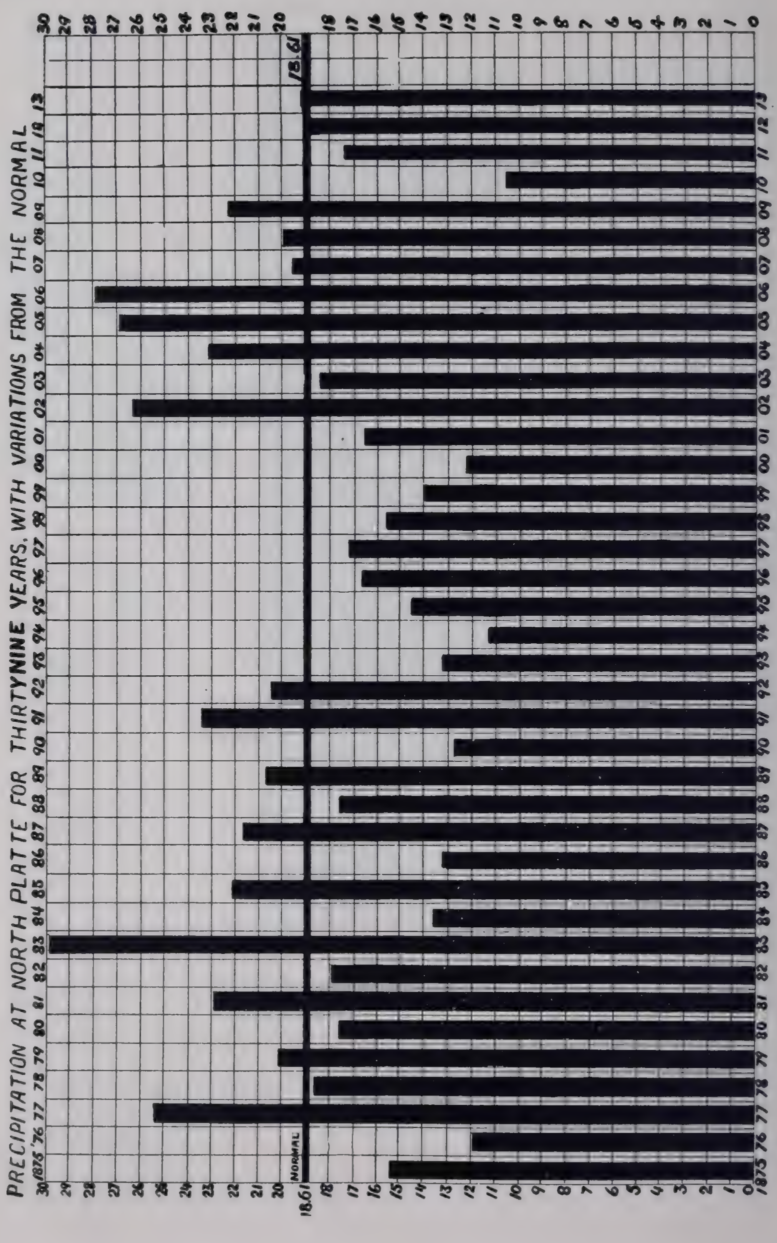


Fig. 2.—Precipitation at North Platte, Nebr., by years, 1875-1913.

TABLE 32.—*Record of precipitation by months, for thirty-nine years, at North Platte, Nebraska, as reported by the United States Weather Bureau.*

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total	Departure from normal
1875	.24	.26	.40	6.21	1.69	1.62	2.12	.66	1.40	.14	.52	.09	15.35	—3.26
1876	.09	.13	.49	.51	2.97	.49	1.16	2.46	1.47	1.07	.49	.51	11.84	—6.77
1877	1.38	.37	.19	.37	3.22	2.99	2.04	5.03	4.49	1.23	.30	3.86	25.47	+6.86
1878	.00	.18	1.40	1.15	3.24	5.85	3.58	1.52	.91	.13	.46	.20	18.62	+ .01
1879	2.33	.43	.11	1.92	2.25	3.31	8.47	.16	.40	.21	.10	.37	20.06	+1.45
1880	.03	.03	.18	.16	2.28	3.12	2.87	3.96	1.53	2.72	.23	.37	17.48	—1.13
1881	.16	.76	1.26	.87	4.84	6.12	3.09	.75	2.36	2.22	.37	.13	22.93	+4.32
1882	.46	.13	.04	1.94	3.98	4.84	2.65	1.68	.28	1.23	.01	.71	17.95	— .66
1883	1.20	1.38	.47	3.02	4.07	7.49	1.34	4.51	1.08	3.47	.42	1.43	29.88	+11.27
1884	.10	.23	1.86	2.14	2.40	1.39	2.19	2.13	.08	.74	.04	.27	13.57	—5.04
1885	.12	.16	.37	1.59	3.31	3.79	3.12	4.87	.86	1.18	1.71	.95	22.03	+3.42
1886	.09	.17	.63	2.09	3.67	1.14	.68	1.99	1.22	.59	.43	.40	13.10	—5.51
1887	.15	.49	.22	3.41	.81	3.20	3.05	4.61	5.10	.15	.19	.30	21.68	+3.07
1888	.09	.42	1.44	2.36	4.93	2.76	2.61	.65	.58	1.12	.08	.42	17.46	—1.15
1889	.97	.07	.62	2.65	2.71	1.95	6.01	2.06	2.57	.31	.20	.54	20.66	+2.05
1890	.35	.38	.27	4.46	.90	2.06	.39	2.42	.19	.84	.42	.03	12.71	—5.90
1891	.65	.49	2.19	2.58	1.69	7.19	3.91	2.45	.87	.57	.08	.69	23.36	+4.75
1892	1.04	.97	.61	4.30	3.70	.60	3.59	3.01	.56	1.49	.08	.42	20.37	+1.76
1893	.03	.62	1.29	.15	1.33	4.11	1.13	3.62	.32	.05	.11	.40	13.16	—5.45
1894	.33	.29	1.72	1.64	.39	3.54	2.39	.17	.14	.59	.01	T.*	11.21	—7.40
1895	.14	.84	.09	1.93	2.38	4.35	1.08	2.13	.48	.09	.96	.11	14.58	—4.03
1896	.27	.06	.87	3.44	1.47	2.76	1.86	2.07	1.84	1.51	.16	.21	16.52	—2.09
1897	.47	.46	.66	2.59	.11	1.72	1.85	3.05	.59	4.11	.85	.63	17.09	—1.52
1898	.77	.19	.64	1.42	4.12	2.54	1.29	1.40	2.56	.07	.51	.03	15.54	—3.07
1899	.11	.36	.83	.82	3.58	1.95	2.04	1.83	.28	.28	1.59	.32	13.99	—4.62
1900	.06	.78	.26	3.34	.90	1.42	3.37	1.37	.25	.39	.09	.06	12.29	—6.32
1901	.04	.44	1.53	2.53	1.83	3.69	.34	2.00	3.14	.41	.30	.19	16.44	—2.17
1902	.40	.35	1.42	.92	7.98	3.46	4.56	1.74	3.34	1.32	T.	.78	26.27	+7.66
1903	.27	1.29	.12	.95	3.74	3.99	2.93	3.58	.76	.44	.28	.01	18.36	— .25
1904	.32	.06	.52	1.52	3.63	4.43	4.90	3.25	2.40	1.92	.03	.19	23.17	+4.56
1905	.90	.69	2.15	3.78	4.56	7.63	2.58	1.57	1.23	1.05	.67	T.	26.81	+8.20
1906	.61	.80	2.22	2.89	2.82	.68	3.14	5.56	4.25	3.05	1.01	.96	27.99	+9.38
1907	.39	.51	.10	.43	2.40	2.69	6.79	2.14	2.91	.14	.31	.80	19.61	+1.00
1908	.16	.78	.20	.64	3.95	5.07	3.17	1.57	.24	3.39	.59	.20	19.96	+1.35
1909	.29	1.61	.98	.72	2.32	5.46	5.21	1.24	.77	.20	2.24	1.37	22.41	+3.80
1910	.34	.02	.19	.48	2.59	2.75	.50	2.02	.97	.01	.11	.72	10.70	—7.91
1911	.28	.39	.20	2.48	1.73	1.13	3.31	2.19	1.37	3.66	.04	.65	17.43	—1.18
1912	.74	.81	3.08	2.93	1.93	.57	4.01	1.27	2.04	1.12	.01	.18	18.69	+ .08
1913	.16	.94	1.68	2.07	3.50	2.13	3.37	.98	.90	.14	.14	3.09	19.10	......
Average	.42+	.50—	.86—	2.03+	2.82—	3.23+	2.89	2.29+	1.45+	1.11+	.41+	.58—	18.61	+ .49

*T. indicates "trace;" less than one one-hundredth of an inch.

TABLE 33.—*Daily precipitation from March 1 to June 30, 1908-1913.*

Day	March						April						May						June					
	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913
1					.18					T.					.48			T.	.09	.46	T.	.01		
2					.53							.01			.17	.11		T.	T.	.13	.07			.40
3								T.		.10		.51	.12			.10	.17		T.		.42			.04
4	T.*					T.			T.	.18			1.16		.02	.01	.55				T.			.01
5	.10	T.						.11					.19		.35		.08			.16	.03			T.
6	.04			.01		.01		.23		.01					.01	.05		T.	.25	T.			.07	.06
7	T.	.13		T.			T.											.02	.03	.44	.04			
8					.01							.68						.25	.02	T.	.18	.02	.13	
9			.18									.34	.09					.35	.48	2.12		.01	.10	T.
10		T.			.05							.06	T.		.05	.08	.83	.03		.91	.02			
11		.15			.18					T.				.02	.01			T.	1.24	.23			.15	T.
12	T.	T.						T.					.18						.01				.09	.83
13					.40	.47			.10	T.			.58	.01				.03		T.		.01	.01	.23
14					.18	1.00		.02	.07		.01		.86	.01	.01			.06	.13	.04				
15		T.					.08	T.	.27					.13	T.			T.	.41					T.
16								.22	.02					T.	T.			T.	.08		.16	.63		
17		T.	T.				T.											T.	.44		T.			
18							.43					T.		.03										
19	.06	T.			.35	.03	T.					.01		.09	T.		.11	.02						.53
20		.02			1.14	.15		.12			1.00	T.		.45		.02		.39		T.				
21		T.									.11	.02			.05	.62		T.		.21				
22												.15	T.			.15		.03	1.80					
23		.29			.03	.01	.02	T.				.29	.02	1.11					.07	T.	T.	.08		
24		.38				.01	.11			.05			.59	.02			.02			T.	1.13			T.
25				.01		T.	T.			.98		T.	.(3	T.				.21	T.	.12		.32		
26		T.	T	.18		T.	T.	T.						.13	1.44	.07				.12				
27		T.			.01						1.61	T.	.07						T.	T.				
28		T.					T.	.02			.05		.03		T.	.47			.02			.05		
29		.01	T.					T.		.86				T.		.05				.52				.03
30			.01					T.	.02	.30	.15			.04							.70		.02	
31		T.			.02								.03	.28			.17	2.11						
Total	.20	.98	.19	.20	3.08	1.68	.64	.74	.48	2.48	2.93	2.07	3.95	2.32	2.59	1.73	1.93	3.50	5.07	5.46	2.75	1.13	.57	2.13

*T. indicates "trace;" less than one one-hundredth of an inch.

TABLE 34.—*Daily precipitation from July 1 to October 31, 1908-1913.*

Day	July						August						September						October					
	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913
1	.41	....	....	.16	.13	.28	....	.39	T.	.02	.01	....	....	.30	T.	....	....	....	....	....	....	.22	....	T.
2	.01	....	....	.08	.02	T.	....	.08	T.	.11	.66	....	....	....	T.	....	....	.01	....	....	T.	.02	....	....
3	....	....	....	.02	.36	....	....	....	....	....	....	....	....	....	.08	.38	....	....	....	....	....	.02	....	....
4	....	....	T.	....	.21	..	....	....	.28	.68	....	....	....	.40	.07	....	....	....	....	....	....	.01	....	....
5	.22	.11	.41	.18	....	....	.01	....	.41	....	....	....	....	.02	....	....	....	....	....	....	....	2.61	....	....
6	.66	....	..	....	....	.05	.34	....	.04	.84	....	.02	....	....	....	....	....	....	....	....	....	....	....	T.
7	....	T.*	....	.10	....	.09	....	T.	.19	....	.14	....	....	.01	....	.09	....	T.	.05	T.	....	....	....	....
8	....	T.	....	.50	....	.61	....	.02	T.	....	....	....	....	....	....	....	....	....	....	.19	....	....	.32	....
9	....	2.35	....	....	....	....	.21	....	....	....	....	.04	....	....	....	.61	.27	.01	....	....	....	....	....	....
10	....	.77	....	....	....	.66	T.	.08	....	.01	....	....	....	....	....	....	.18	T.	....	....	....	....	.11	T.
11	.01	.14	.04	....	....	....	.01	.58	....	.34	....	....	....	....	....	....	.57	....	....	.01	....	....	.28	....
12	.68	....	....	.42	....	....	.02	....	.57	....	....	.13	....	....	.08	....	.23	....	....	....	....	....	....	....
13	T.	....	....	....	....	....	.22	....	.01	.01	....	.01	....	.01	....	....	.52	....	....	....	....	....	....	....
14	.02	....	....	.03	....	....	.02	.06	....	....	....	....	T.	.03	.07	.01	.14	....	....	....	....	....	....	....
15	T.	.28	....	.16	....	T.	T.	....	....	....	.45	....	....	....	....	.04	.01	T.	....	....	....	.61	....	....
16	T.	.19	....	....	....	....	T.	....	.25	.13	.01	....	....	....	....	....	....	.61	....	....	....	.13	....	.04
17	....	....	....	.22	....	.30	....	T.	.16	.05	....	....	....	....	....	....	....	.09	....	....	T.	....	....	.02
18	.06	....	....	....	1.07	.88	.34	....	....	....	....	....	....	....	T.	.04	....	....	.10	....	.01	....	....	....
19	.14	....	.03	T.	....	....	....	.03	....	....	....	.61	..	....	....	....	.03	T.	3.24	T.	....	....	....	....
20	....	....	....	....	.39	....	....	....	....	....	....	....	....	T.	....	.07	.04	....	....	T.	....	....	....	....
21	....	T.	T.	....	....	....	....	....	....	....	....	.17	....	T.	.04	....	....	....	....	....	....	....	....	.02
22	.79	....	....	.80	....	....	.03	....	....	....	....	....	T.	....	T.	....	....	T.	....	....	....	....	....	....
23	T.	....	T.	....	....	T.	.09	....	....	....	....	....	....	....	.42	....	....	.12	....	....	....	....	....	....
24	.03	.07	....	....	....	.10	T.	T.	.06	....	....	....	....	....	....	.06	....	.03	....	....	....	....	....	T.
25	....	.01	....	....	.07	....	.01	....	....	....	....	....	.24	....	.21	....	....	....	T.	....	....	....	.01	....
26	T.	....	....	T.	1.10	....	.05	....	....	....	....	....	T.	....	....	....	....	....	....	....	....	.04	.08	....
27	.14	T.	T.	....	....	.40	T.	....	....	....	....	....	....	....	....	....	.05	.02	....	....	....	....	..	.06
28	....	....	T.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.01	....	....	....	....	....	....
29	....	1.18	.02	.64	....	....	....	....	.05	....	....	....	....	....	....	.02	....	....	....	....	....	....	....	....
30	....	.10	T.	....	.62	T.	.22	....	....	....	....	....	....	....	....	.05	....	....	....	....	....	....	....	....
31	....	.01	....	....	.04	....	....	....	T.	....	....	....	....	....	....	..	....	....	....	....	....	....	.32	....
Total	3.17	5.21	.50	3.31	4.01	3.37	1.57	1.24	2.02	2.19	1.27	0.98	.24	.77	.97	1.37	2.04	.90	3.39	.20	.01	3.66	1.12	.14

*T. indicates "trace;" less than one one-hundredth of an inch.

TABLE 35.—*Daily mean temperature from April 1 to August 31, 1908-1913.**

Day	April						May						June						July						August					
	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913
1	25	41	53	43	41	33	49	37	39	34	61	35	57	55	60	77	63	52	56	75	70	82	70	62	78	75	76	68	70	61
2	36	46	58	40	46	31	48	44	36	40	68	32	63	56	60	75	73	55	61	78	68	73	74	68	80	75	77	67	60	63
3	52	50	56	30	54	20	41	58	46	36	59	41	70	63	53	73	62	56	66	77	72	79	76	71	87	73	71	67	62	63
4	48	43	37	30	55	19	34	68	45	42	45	40	66	73	53	79	65	58	75	76	78	86	67	59	77	72	72	65	68	62
5	56	31	49	38	58	36	36	60	47	48	51	43	66	75	60	66	62	62	67	64	73	72	68	64	79	76	61	69	74	63
6	52	31	62	36	40	42	46	52	46	62	58	45	66	63	58	71	52	46	58	70	73	73	77	65	66	79	64	64	69	63
7	31	30	56	39	51	34	50	62	45	58	60	41	60	55	50	84	52	41	64	70	76	80	81	63	68	78	72	74	63	60
8	41	38	59	45	55	26	53	46	66	70	66	46	66	59	61	77	52	46	74	78	76	71	82	58	73	75	63	76	62	69
9	55	45	62	49	54	26	57	47	62	74	64	40	63	63	59	75	54	50	78	67	63	72	72	63	70	76	67	71	65	64
10	50	50	59	53	53	20	61	61	59	50	45	44	60	59	56	68	65	51	78	69	72	78	76	59	72	77	69	70	72	64
11	55	35	62	59	59	22	60	64	48	59	47	47	64	58	61	69	66	60	75	68	60	74	82	51	62	78	75	69	78	65
12	63	35	68	44	56	30	64	58	54	67	50	54	65	60	63	69	64	52	72	72	67	71	75	68	67	75	68	77	72	63
13	67	40	53	37	38	32	55	54	53	73	42	49	63	61	67	76	71	52	70	66	71	68	81	68	69	76	66	78	73	65
14	61	40	40	40	40	34	52	51	47	74	53	38	47	59	73	75	64	63	67	70	78	73	69	67	72	77	70	80	70	69
15	48	46	37	45	41	40	63	55	52	71	51	49	53	66	79	78	64	63	73	72	76	66	65	65	71	80	75	83	66	68
16	51	53	39	56	40	45	70	66	42	71	59	46	64	72	75	65	58	64	76	77	82	68	76	64	75	81	67	77	74	66
17	55	60	41	53	34	50	61	63	55	76	67	46	62	69	67	68	53	63	67	76	80	67	65	62	67	70	58	76	76	66
18	65	34	43	48	42	42	66	58	61	72	71	57	62	71	81	71	55	64	66	78	74	69	62	56	65	69	65	72	74	67
19	66	36	56	50	48	46	72	61	66	53	66	43	70	73	80	76	63	62	64	80	75	62	77	58	68	68	72	76	72	68
20	63	31	70	55	40	50	54	58	50	47	51	39	78	68	81	77	69	63	74	68	76	74	70	59	64	73	79	73	66	68
21	58	31	48	60	36	50	54	59	43	49	55	42	82	69	82	80	67	57	71	66	72	74	76	62	64	80	81	66	71	52
22	68	42	46	55	47	33	62	61	57	53	63	43	71	72	81	81	65	62	69	69	80	70	85	60	58	79	71	56	72	58
23	54	50	43	49	53	32	53	56	56	66	65	55	64	69	83	79	65	61	73	64	77	61	80	57	62	83	75	58	77	60
24	52	51	46	46	55	31	54	49	59	74	67	54	70	67	68	84	72	61	74	67	81	62	79	55	65	73	54	56	78	64
25	47	59	53	46	55	33	60	49	60	77	75	53	72	70	68	74	80	64	76	72	81	70	69	58	74	77	53	67	81	59
26	36	50	61	58	51	38	66	48	53	63	73	59	75	75	71	66	80	72	76	71	85	77	71	62	64	81	64	65	74	61
27	39	49	61	59	45	11	59	65	58	58	65	59	72	79	72	77	80	73	77	72	84	79	78	58	70	74	77	58	79	67
28	34	55	76	56	46	45	54	75	61	50	60	61	56	80	75	86	80	70	79	77	73	75	76	64	74	62	72	61	76	53
29	46	33	59	46	51	50	54	58	67	60	67	60	66	70	76	88	80	58	78	73	70	74	77	64	79	65	72	69	79	63
30	48	26	53	31	53	38	58	56	68	67	74	59	66	73	68	87	76	57	69	74	74	74	72	49	74	72	60	71	64	56
31	....	....	....	....	....	....	52	53	65	71	52	57	....	....	....	....	....	....	71	71	78	70	66	51	61	71	61	77	72	69
Av.	50.7	42	53.5	46.5	47.9	36	55.4	56.5	53.7	60.2	59.7	48	65.3	67	68	75.7	65.7	59	70.8	71.8	74.8	72.4	74	61	70.2	74.8	68.6	69.6	71.3	63

*In cooperation with the office of Physical Investigations, Bureau of Plant Industry, Washington, D. C.

TABLE 36.—*Daily evaporation from April 1 to August 31, 1908-1913.**

Day	April						May						June						July						August					
	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913
1	....	....	.289	.172	a	a	.281	.366	.038	.010	.248	.209	.090	.048	.254	.497	.223	.329	.126	.226	.239	.371	.257	.335	.331	.193	.382	.337	.292	.339
2	....	....	.310	.150	a	a	.360	.166	.135	.081	.299	.063	.067	.061	.458	.298	.325	.347	.158	.265	.187	.347	.277	.491	.357	.210	.288	.285	.111	.443
3	....	.235	.342	.185	a	a	.130	.208	.124	.016	.277	.139	.159	.145	.116	.185	.340	.153	.242	.336	.336	.389	.442	.342	.369	.264	.594	.285	.151	.503
4	.190	.134	.127	.185	a	a	....	.296	.057	....	.177	.240	.356	.317	.046	.458	.318	.290	.282	.308	.313	.459	.202	.371	.339	.256	.346	.357	.174	.485
5	.241	.051	.193	.102	a	1.047	.046	.474	.010	.086	.138	.190	.223	.290	.152	.378	.288	.232	.321	.125	.288	.351	.238	.427	.319	.278	.080	.248	.195	.389
6	.171	.008	.386	.148	a	a	.089	.300	.011	.095	.171	.213	.296	.201	.248	.359	.078	.198	.160	.127	.447	.289	.343	.391	.306	.303	.117	.189	.204	.323
7	.101	.140	.248	.139	a	a	.168	.118	.103	.189	.155	.233	.243	.101	.077	.400	.102	.273	.188	.097	.369	.435	.313	.176	.155	.247	.286	.247	.186	.346
8	.227	.152	.265	.241	a	a	.258	.334	.174	.308	.225	.238	.168	.106	.202	.276	.036	.238	.145	.223	.328	.370	.355	.450	.156	.261	.152	.156	.185	.401
9	....	.199	.223	.264	a	a	.265	.232	.327	.373	.366	.074	.016	.268	.224	.401	.016	.245	.287	.061	.292	.239	.398	.450	.264	.326	.260	.177	.210	.283
10	.176	.198	.185	.132	.695	1.358	.168	.410	.274	.275	.093	.035	.165	.104	.168	.379	.017	.236	.302	.290	.388	.390	.368	.341	.185	.208	.288	.212	244	153
11	.285	.147	.223	.249	a	a	.391	.284	.150	.211	.178	a	.327	.102	.287	.073	.145	.089	.369	.290	.164	.436	.319	.355	.202	.351	.195	.201	.440	.277
12	.245	.229	.213	.305	a	a	.229	.233	.118	.369	.142	.151	.277	.161	.382	.699	.076	.277	.183	.299	.325	.486	.299	.361	.269	.181	.166	.272	.248	.352
13	.326	.107	....	.170	.483	a	.230	.229	.253	.411	.063	.261	.276	.126	.415	.583	.270	.198	.200	.281	.311	.240	.347	.364	.249	.203	.110	.304	.394	.267
14	.354	.123	.151	.206	.244	a	.259	.105	.136	.309	.221	.243	.087	.117	.493	.503	.307	.272	.124	.224	.263	.284	.465	.300	.150	.333	.189	.285	.236	.420
15	.299	.150	.222	.234	.137	.536	.208	.221	.278	.512	.267	.077	.020	.214	.425	.465	.200	.401	.216	.302	.330	.137	.340	.398	.127	.241	.330	.421	.028	.479
16	.092	.170	.174	.279	.166	.252	.302	.373	.224	.363	.195	.239	.070	.191	.394	.183	.230	.395	.285	.192	.359	.244	.302	.307	.244	.281	.343	.282	.193	.526
17	.086	.216	.229	.170	.142	.252	.180	.295	.254	.443	.202	.261	.215	.281	.290	.209	.166	.353	.332	.337	.390	.260	.303	.343	.075	.246	.209	.294	.275	.455
18	.176	.172	.244	.249	.101	.195	.298	.150	.274	.596	.346	.308	.195	.260	.411	.319	.222	.388	.175	.364	.469	.190	.089	.205	.142	.150	.017	.333	.226	.454
19	.230	.128	.225	.213	.121	.183	433	.220	.284	.242	.158	.324	.288	.291	.456	.466	.217	.225	.182	.374	.254	.168	.234	.252	.266	.176	.234	.222	.261	.375
20	.247	.008	.322	.225	.086	.275	.462	.142	.270	.206	.308	.141	.235	.214	.557	.513	.300	.169	.189	.336	.362	.202	.178	.316	.229	.267	.231	.211	.123	.416
21	.216	.165	.374	.313	.080	.176	.295	.266	.085	.077	.219	.121	.285	.188	.429	.544	.344	.244	.343	.333	.368	.262	.281	.353	.271	.349	.261	.430	.236	.257
22	.255	.051	.256	.316	.089	.226	.298	.184	.165	.057	.197	.242	.271	.280	.673	.496	.262	.346	.183	.230	.334	.327	.448	.310	.071	.325	.285	.174	.290	.335
23	.235	.181	.355	.208	.189	.140	.009	.090	.289	.244	.196	.259	.371	.316	.466	.319	.303	.294	.243	.323	.408	.360	.253	.162	.095	.518	.227	.194	.329	.334
24	.306	.182	.251	.103	.336	.174	....	.148	.295	.287	.399	.283	.224	.218	.271	.560	.288	.283	.319	.300	.439	.253	.365	.185	.052	.239	.330	.079	.253	.366
25	.262	.277	.240	.044	.207	.143	.107	.066	.314	.451	.289	.162	.319	.234	.131	.342	.291	.325	.250	.101	.061	.351	.140	.296	.036	.307	.225	.272	.328	.353
26	.176	.255	.251	.152	.274	.197	.279	.063	.061	.328	.310	.252	.289	.303	.253	.295	.430	.457	.109	.231	.511	.247	.093	.375	.277	.374	.314	.279	.312	.460
27	.231	.241	.344	.264	.213	.304	.186	.214	.152	.289	.376	.398	.259	.259	.340	.471	.464	.561	.274	.122	.363	.462	.226	.361	.155	.349	.238	.181	.315	.392
28	.157	.143	.353	.036	.074	.440	.316	.383	.184	.068	.381	.325	.102	.354	.459	.536	.437	.617	.394	.295	.258	.359	.263	.283	.296	.299	.173	.295	.361	.303
29	.176	.236	.350	.227	.148	.378	.172	.306	.236	.007	.282	.374	277	.209	.490	.669	.444	373	.307	.335	.094	.435	.348	.341	.382	.284	.306	.315	.299	.369
30	.199	.020	.144	.018	.133	.386	.324	.439	.311	.126	.408	.347	.086	.164	.334	.609	.390	.411	.294	.303	.192	.256	.270	.374	.317	.249	.239	.201	.216	.277
31	....	....	....	....	....	....	.111	.037	.390	.184	.250	.224	....	....	....	....	....	....	.331	.223	.305	.259	.209	.371	.246	.071	.188	.355	.140	.426
Av.	.217	.154	.258	.190	.206	.222	.228	.237	.193	.233	.243	.214	.208	.204	.330	.416	.251	.307	.242	.253	.314	.318	.289	.335	.223	.269	.245	.261	.240	.373

*In cooperation with the office of Physical Investigations, Bureau of Plant Industry, Washington, D. C.

TABLE 37.—*Daily wind velocity per hour from April 1 to August 31, 1908-1913.**

Day	April						May						June						July						August					
	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913	1908	1909	1910	1911	1912	1913
1	....	5.9	12.3	11.8	6.9	10.2	8.8	9.3	8.2	5.9	14.3	10.7	10.2	3.7	10.8	13.1	6.0	7.0	3.3	4.3	6.8	7.6	5.8	10.6	8.1	9.0	6.2	9.5	8.2	6.0
2.....	....	8.6	9.3	11.9	5.9	15.5	15.9	7.0	6.1	11.2	7.2	5.8	11.4	6.5	14.1	6.0	8.9	5.3	4.4	4.3	1.1	6.8	7.0	16.0	5.9	4.6	1.4	11.5	7.5	9.2
3.....	9.1	13.6	11.0	5.6	5.8	11.8	16.6	6.5	10.4	5.4	24.2	6.6	17.7	3.8	5.9	3.5	7.9	8.7	8.7	10.3	11.2	10.4	4.8	9.7	8.9	6.1	6.3	5.5	10.5	8.3
4......	6.3	7.7	11.7	4.8	4.2	4.8	12.3	6.2	18.8	11.4	8.1	6.9	8.4	7.5	4.5	10.4	12.3	10.6	7.2	7.4	8.9	6.9	8.0	5.6	9.9	7.2	8.4	8.7	9.8	7.7
5......	8.8	6.5	6.8	10.4	13.0	6.8	7.9	13.7	10.5	15.7	5.9	5.9	7.5	7.4	8.7	6.7	7.3	5.6	7.1	2.8	4.3	7.7	6.1	7.9	6.9	8.3	6.8	9.9	3.8	8.5
6......	15.1	6.4	13.7	9.4	13.0	9.9	3.9	10.1	5.4	14.3	4.6	13.2	7.9	8.0	14.8	12.1	4.4	5.4	9.3	8.2	8.1	8.7	9.3	11.3	10.6	9.4	6.5	6.2	4.9	8.1
7......	8.4	7.3	6.5	6.2	9.5	14.4	5.3	8.1	5.8	7.7	7.9	12.8	8.0	5.5	13.2	10.4	11.5	7.3	4.3	5.1	7.3	13.3	7.4	4.5	3.2	6.9	7.9	7.8	4.2	5.0
8......	7.4	6.6	7.0	12.2	10.5	13.7	8.8	6.1	6.1	7.9	4.6	13.1	4.7	5.1	9.0	5.5	15.7	8.0	3.9	7.2	7.0	9.3	7.9	4.8	5.2	6.2	4.3	6.3	3.7	7.0
9......	7.0	9.8	9.3	19.1	4.8	22.5	13.6	9.9	10.1	7.4	7.3	10.7	6.3	7.7	12.0	8.1	14.2	12.0	5.2	7.1	5.2	7.4	5.4	9.6	8.2	9.1	5.2	7.8	4.2	8.5
10......	5.8	7.7	6.9	6.3	9.5	19.0	5.3	21.4	8.1	12.0	15.9	9.9	7.4	5.6	4.0	7.6	6.3	13.2	4.4	8.8	9.3	7.8	10.3	12.9	5.7	8.6	9.6	7.2	7.3	4.4
11......	12.1	7.5	5.8	8.2	6.4	4.2	9.3	10.4	4.1	8.4	6.8	5.3	9.5	4.5	8.6	7.1	7.2	13.5	5.7	5.8	5.0	10.7	5.3	7.6	6.1	4.2	8.2	7.1	4.2	6.4
12......	5.7	9.1	12.5	12.7	14.5	4.0	9.7	5.7	7.7	13.4	6.9	12.9	4.3	4.1	11.9	4.2	8.3	11.0	3.1	3.8	8.2	9.2	4.4	9.8	4.2	4.1	5.3	8.2	5.7	9.0
13.....	10.3	7.6	15.3	7.7	17.7	3.4	9.9	8.5	9.8	15.3	7.5	13.2	7.3	3.7	12.4	17.8	6.7	6.9	4.5	7.7	12.2	5.7	8.3	5.8	11.8	2.9	4.9	6.4	9.0	5.4
14......	12.3	7.5	12.7	6.0	14.7	5.1	10.1	5.9	15.5	14.2	12.9	8.1	11.4	6.0	20.0	17.0	6.8	6.8	7.9	5.6	3.5	8.6	7.5	6.5	6.0	4.8	4.8	4.5	6.8	8.8
15......	10.5	9.9	15.1	5.8	6.5	7.9	7.2	8.4	8.5	15.7	7.3	5.5	15.5	9.7	13.4	9.8	5.0	7.5	6.3	5.9	4.6	5.0	6.1	8.6	2.6	4.3	7.7	8.9	9.5	7.5
16......	10.3	8.6	16.1	8.8	4.4	5.6	10.6	16.6	11.8	8.7	6.2	8.7	4.9	3.9	14.2	6.1	5.2	9.8	5.5	5.7	4.3	7.7	6.6	7.1	3.7	4.7	9.6	6.6	3.8	11.4
17.....	5.6	7.3	19.2	10.4	4.8	6.6	4.0	5.8	5.2	10.9	5.0	8.8	8.1	7.0	6.1	4.6	3.4	9.0	4.7	11.8	7.9	8.8	10.0	5.0	7.9	2.9	5.4	6.6	7.0	11.4
18......	5.1	7.2	9.1	6.5	4.0	10.5	5.3	5.1	13.2	11.5	15.1	18.2	8.1	7.1	9.9	4.8	4.1	9.8	3.1	11.4	12.3	5.0	8.5	6.0	5.4	2.9	3.4	11.3	2.6	10.3
19	1.8	6.0	6.6	4.8	13.0	14.4	11.8	7.6	4.9	9.1	8.8	10.1	10.5	10.3	9.8	9.7	3.6	5.8	5.4	13.1	7.2	7.1	7.5	4.3	5.2	3.5	11.2	8.5	4.2	8.0
20	5.6	7.7	12.0	5.3	11.4	11.1	12.0	5.8	10.5	9.7	7.9	4.5	6.2	5.6	15.1	13.6	6.2	3.9	2.8	8.2	7.5	4.6	3.8	5.6	5.6	7.7	4.9	7.3	1.9	7.3
21......	7.5	8.0	15.2	13.1	9.4	11.3	3.5	9.3	6.0	11.3	4.5	3.8	7.6	4.6	11.9	13.3	10.9	5.5	8.5	2.8	6.2	9.4	10.9	7.5	6.0	10.5	3.7	8.1	3.4	5.8
22......	13.4	6.1	10.8	13.7	6.2	12.2	10.9	10.9	3.9	4.7	7.7	7.0	6.8	5.6	16.8	9.0	7.9	8.6	6.7	5.0	8.4	8.4	12.6	6.3	5.0	10.8	3.2	5.8	4.7	7.2
23......	17.9	7.9	12.6	11.2	5.9	14.5	8.5	7.0	6.1	12.6	5.1	7.7	4.8	6.7	14.8	11.1	8.2	8.9	6.7	7.1	6.4	5.7	4.2	4.1	7.4	11.6	5.1	8.1	5.1	3.8
24......	15.1	5.6	6.6	13.5	17.5	8.0	4.9	9.1	6.9	6.0	9.1	8.5	6.4	4.9	8.2	11.1	7.5	3.9	12.0	9.9	9.1	8.5	7.9	6.9	9.7	5.6	10.1	3.5	2.3	5.7
25......	11.9	9.0	4.9	13.4	12.7	7.4	4.8	5.2	12.3	15.4	13.0	2.6	12.8	8.2	2.9	10.0	3.3	7.0	10.6	3.0	5.1	7.6	6.4	5.1	10.9	4.8	6.7	10.3	4.1	4.9
26......	19.4	7.7	6.1	16.2	10.0	7.9	8.4	5.3	6.7	13.1	10.1	4.5	11.2	7.7	3.3	5.3	9.1	11.1	6.2	7.1	11.3	10.4	7.1	7.3	4.7	8.0	12.3	6.5	8.6	7.8
27......	10.6	14.9	14.0	16.7	13.2	15.7	6.7	12.0	10.7	9.4	15.7	8.4	3.2	8.2	7.0	14.5	10.4	15.2	3.8	4.9	6.7	6.3	4.5	7.6	3.6	5.7	7.6	4.9	6.5	6.1
28......	9.5	7.0	8.3	4.9	6.6	15.8	7.3	14.7	2.7	11.6	10.6	3.5	2.9	8.9	14.4	13.7	9.6	17.7	10.6	4.2	6.7	5.6	6.1	5.8	8.8	6.6	8.1	12.1	8.7	3.9
29.....	5.4	17.0	10.8	11.7	14.6	14.5	5.0	12.9	8.5	10.4	10.9	8.6	9.8	5.5	14.4	17.8	10.9	7.2	4.7	9.1	1.7	11.9	7.9	7.8	10.8	11.9	7.4	14.8	7.6	6.8
30......	5.4	12.6	5.1	15.9	7.1	12.7	14.7	18.5	5.9	4.3	17.1	8.0	2.1	3.2	7.1	18.9	11.1	7.2	5.1	7.0	4.3	6.8	5.2	5.8	16.2	6.5	5.5	4.0	6.7	4.4
31	....	....	....	....	....	....	21.0	7.2	7.8	11.8	6.7	4.3	....	....	....	....	....	....	7.0	10.0	7.3	4.1	4.9	5.4	3.5	12.8	9.8	7.5	3.2	6.6
Av.	8.8	8.5	10.5	10.1	9.4	10.7	9.2	9.3	8.3	10.5	9.5	8.3	8.1	6.2	10.6	10.1	8.0	8.6	6.1	7.0	7.0	7.8	7.0	7.4	7.0	6.8	6.8	7.8	5.8	7.3

*In cooperation with the office of Physical Investigations, Bureau of Plant Industry, Washington, D. C.

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OF
NEBRASKA.

TRANSPIRATION AS A FACTOR IN CROP PRODUCTION.

BY T. A. KIESSELBACH.

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CONTENTS.

PAGE
Summary 12
Part I—General survey 19
  Meaning of transpiration 19
  Character of past work 20
  Outline of method principles for studying transpiration . 21
  Basis of comparison 22
  Methods of determining transpiration:
    The cobalt method 22
    Field estimates 23
    Collection of transpired water 23
    The potometer method 24
      Measuring the intake of water 24
      Loss in weight 24
      Character of plant 25
        Plant cuttings 25
        Rooted plants 25
    Summary of discussion on method principles 26
  Determining the transpiration of field crops 26
  Sources of error in potometer tests 26
    Outline of factors influencing transpiration determinations with rooted plants in pots as sources of experimental error 27
    Discussion of sources of error in potometer tests . . . 27
      Character of potometer and contents 27
      Limitation of soil fertility 29
      Improper distribution of soil moisture 30
      Evaporation from surface of soil 30
      Entrance of rainfall 31
      Exposure of potometer to atmosphere 31
      Unintentional lack of uniformity in the soil . . . 31
      Environment 32
      The plant 32
      Stage of maturity 33
      Errors due to methods of computation 33
  Investigators who have studied transpiration in relation to crop yields, based upon plants grown beyond the seedling stage 36
  Factors influencing transpiration in fact 38
    Outline of factors influencing transpiration in fact. 39

PAGE
Part II. The experiments 41
  Problems under investigation 41
  Methods of compiling data 41
  Methods of determining the yield and leaf-area 43
  Methods of investigation 43
    Location of experiments and maturity of plants 43
    Description of potometers used 43
      Potometer with coil-watering device 44
      Potometer with subirrigation-watering device 48
      Laboratory potometer 50
  Relative growth in field potometers and in field 50
  Distribution of moisture in soil 50
  Water loss by evaporation from the potometers 52
  Effect of size of potometer as a source of experimental error 54
  Effect of exposure of potometer on the growth and water requirements of corn 67
  Variation in results from similar potometers and the reduction of error by repetition 71
  The relation of climate to transpiration:
    Hourly transpiration and evaporation in relation to climatic factors 87
    Relative day and night transpiration and evaporation in relation to climatic factors 93
    Daily transpiration and evaporation in relation to climatic factors 95
    Variation in the daily transpiration rate as influenced by the soil-moisture content 100
    Variation in weekly transpiration in relation to climatic factors 105
    Variation in yearly transpiration 107
    Relation of transpiration to atmospheric humidity 111
  Effect of previous condition of growth on transpiration 111
  Effect of transpiration on leaf temperature 115
  Relative rates of evaporation from equal areas of free water surface and leaves of growing corn plants 117
  The growing crop as a protection against water-dissipating influences 118
    Evaporation studies in corn and small-grain fields 118
    Relative wind velocities 3 feet and 10 feet above the ground in a cornfield 124
  Method study with free-water-surface evaporation jars 125

PAGE
Relation of available soil-moisture content to growth and water requirements of corn 127
  Plan of the experiments 127
  Degrees of soil moisture maintained 127
  Discussion of results 129
    Effect of deficiency of soil moisture 131
    Effect of an overabundance of soil moisture . . . 141
  Effect of increasing the fertility of soils differing in moisture content 142
Relation of soil fertility to growth and water requirements of corn 143
  Results of the two soil fertility experiments—1911 and 1914 145
    Discussion of results 153
Effect of prolonged confinement in cans of soils differing in fertility 157
Influence of acclimatization, variety, and kind of crop upon the transpiration relationships 159
  Acclimatization 159
  Difference in growth habits 166
  Erectness of leaves 167
  Special drouth-resistant corn 167
  Sorghums 168
  Weeds 169
Relation of ash content to transpiration under various conditions of growth 170
  Effect of climatic differences upon relation of transpiration to ash content 170
  Effect of differences in soil fertility upon relation of transpiration to ash content 175
  Effect of a difference in soil moisture content upon relation of transpiration to ash content 180
  Effect of size of potometer upon relation of transpiration to ash content 180
  Effect of kind of crop and variety upon relation of transpiration to ash content 182
Correlative response of leaf structure and transpiration, as related to variety, acclimatization, and soil conditions 184
Tissues concerned in the transpiration current of corn . . . 188
  Technique 188
  Tissue structure 189
Part III. Application 200
Literature cited 209

TABLES.

TABLE PAGE
1. Relative development of corn plants in the potometers and in the field 51
2. Distribution of moisture in potometers with the two methods of water addition used in the Nebraska experiments 53
3. Amount of water lost from check potometers in which no plants were grown but otherwise treated the same as the cropped potometers 53
4. Effect of size of potometer upon growth and water requirements of corn. 1914 58
5. Effect in per cent of applying manure to potometers of different sizes. Results with manure are here expressed in per cent of results without manure 61
6. Effect in per cent of increasing size of potometer 61
7. Summary showing effect of size of potometer upon growth and water requirements of corn. 1914 62
8. Summary showing effect of size of potometer upon growth and water requirements of corn. 1913 63
9. Effect of degree of exposure of potometer upon growth and water requirements of corn 68
10. Summary of effect of degree of exposure of potometer upon growth and water requirements of corn. 1914 69
11. Summary showing effect of degree of exposure of potometers upon their soil temperatures 70
12. Results from 48 plants grown in potometers in 1912 to study variation in water requirements 74
13. Coefficients of variability with dry weight of stalks in similar potometers planted with Hogue's Yellow Dent corn 77
14. Coefficients of variability with dry weight of ear in similar potometers planted with Hogue's Yellow Dent corn 78
15. Coefficients of variability with dry weight of leaves in similar potometers planted with Hogue's Yellow Dent corn 79
16. Coefficients of variability with total dry weight of plant in similar potometers planted with Hogue's Yellow Dent corn 80
17. Coefficients of variability with leaf-area per plant in similar potometers planted with Hogue's Yellow Dent corn 81

TABLE PAGE
18. Coefficients of variability with total transpiration per plant in similar potometers planted with Hogue's Yellow Dent corn....82
19. Coefficients of variability with water used per gram of dry weight of ear in similar potometers planted with Hogue's Yellow Dent corn....83
20. Coefficients of variability with water transpired per gram of dry weight of crop in similar potometers planted with Hogue's Yellow Dent corn....84
21. Coefficients of variability with water used per square inch of leaf-area in similar potometers planted with Hogue's Yellow Dent corn....85
22. Summary showing coefficients of variability for 48 similar potometers in 1912 and 80 potometers in 1913....86
23. Summary of transpiration, free-water-surface evaporation, and weather factors during successive hours of the day and night. 1910....88
24. Summary of transpiration, free-water-surface evaporation, and weather factors during successive hours of the day and night. 1914....89
25. The data of Table 23 are here so calculated as to show the per cent increase or decrease in the transpiration and evaporation rates for each hour of the day over those of the preceding hour. The actual hourly increase or decrease in the weather factors is also given. Average for 30 days. 1914....92
26. Average relative day and night transpiration and evaporation rates during nine consecutive days in 1910 and 30 days in 1914....94
27. Relationship between the daily transpiration, evaporation, and climatic factors. 1910....96
28. Relationship between the daily transpiration, evaporation, and climatic factors. 1914....97
29. Relative daily transpiration from plants in different degrees of soil saturation. 1913....101
30. Relative daily transpiration from plants in different degrees of soil saturation. 1914....102
31. Weekly summary of transpiration from corn plants and weather factors thruout the growing season. 1914....105
32. Weekly summary of water transpired thruout the growing season by corn plants growing in four different degrees of soil saturation. 1914....106

TABLE PAGE
33. Seasonal variation in water requirement of corn as related to climatic conditions in different years expressed in free-water-surface evaporation. 1910-1914 . . . 109
34. Mean weather factors (7 a. m. to 6 p. m.) during July and August for five years. 1910-1914 . . . 109
35. Effect of seasonal climatic differences upon water requirements of corn exposed under natural conditions, as compared with effect of controlled climatic differences under greenhouse conditions . . . 110
36. Relation of water used by plants to atmospheric humidity. 1911. Hogue's Yellow Dent corn used. Grown in potometers 16″x36″. Harvested at silking stage . . . 112
37. Relation of water used by plants to atmospheric humidity. 1912. Hogue's Yellow Dent corn used. Grown in potometers 16″x36″. Harvested at silking stage . . . 112
38. Relation of water used by plants to atmospheric humidity. 1912. Pop corn used. Grown in 4-gallon potometers. Harvested at silking stage . . . 113
39. Relation of water used by corn plants to atmospheric humidity. Average of three tests in 1911 and 1912 . . . 113
40. Effect of previous condition of growth on transpiration. 1912. Pop corn used. Grown in 4-gallon potometers . . . 114
41. Summary of plant temperatures showing the effect of transpiration upon leaf temperature. 1913 . . . 115
42. Summary of plant temperature records in the cornfield. 1912. All temperatures were taken in the shade . . . 116
43. Summary showing the temperature of different parts of the growing corn plant. 1913 . . . 116
44. Weekly summary of evaporation from free water surfaces 36 square inches in area at six elevations in a cornfield. 1912 . . . 120
45. Weekly summary of evaporation from free water surfaces 36 square inches in area at five elevations in a cornfield. 1913 . . . 121
46. Weekly summary of evaporation from free water surfaces 36 square inches in area at five elevations in a cornfield. 1914 . . . 121

TABLE PAGE

47. Evaporation from free water surfaces 36 square inches in area at four elevations in a spring wheat field. 1912 ... 122
48. Weekly summary of evaporation from free water surfaces 36 square inches in area at four elevations in an oat field. 1913 ... 122
49. Weekly summary of evaporation from free water surfaces 36 square inches in area at four elevations in an oat field. Evaporation expressed as percentage of evaporation from the upper jar. 1913 ... 123
50. Summary showing relative free water evaporation rates at different elevations in corn and small-grain fields. 1912-1914 ... 123
51. Summary showing the relative responsiveness of free water surface evaporation from several styles of evaporation jars having 36 square inches of surface area ... 126
52. Various ways of expressing water content of soil in different degrees of saturation, during three years—1910, 1913, and 1914 ... 128
53. Growth relationships and water requirements of corn in five different degrees of soil moisture. 1910 ... 133
54. Growth relationships and water requirements of corn in three different degrees of soil moisture. 1913 ... 134
55. Growth relationships and water requirements of corn in four different degrees of soil moisture, with and without manure. 1914 ... 135
56. Summary showing the growth relationships and water requirements of corn in different degrees of soil moisture, during three years. 1910, 1913, and 1914 ... 137
57. Summary of three years' results with different degrees of soil-moisture content. 1910, 1913, and 1914 ... 138
58. Summary of three years' results with different degrees of soil-moisture content. 1910, 1913, and 1914 ... 139
59. Summary of average analyses of soils used in filling the potometers in the soil fertility series in 1911 and 1914 ... 144
60. Total amount in pounds of nitrogen, acid soluble potash and phosphoric acid contained in the soil of the average potometer in each group of the fertility series. 1911 and 1914 ... 145
61. Summary of data secured from potometers containing soils of six degrees of fertility. 1911 ... 147

TABLE PAGE
62. Summary of data secured from potometers containing soils of six degrees of fertility. 1914 149
63. Summary of average results secured during two years from potometers containing six degrees of soil fertility. 1911 and 1914 151
64. Showing in per cent the effect of applying manure to potometers of different degrees of soil fertility. The results with manure are here expressed in per cent of the results without manure 152
65. Summary showing the relative dry matter and water requirements of corn on the different soil types during two years. 1911 and 1914 154
66. Summary showing plant growth and water requirements of corn in six degrees of soil fertility during four consecutive years. 1911 to 1914. The potometers were filled in 1911 and the same soil remained in them undisturbed thruout the period 157
67. Effect of variety, adaptation, and kind of crop on the water requirement. 1914 161
68. Summary showing the effect of variety, adaptation, and kind of crop on the water requirement. 1914 165
69. Relation of ash content in the corn plant to the amount of transpiration as affected by a difference in atmospheric humidity 171
70. Effect of difference in seasonal climatic conditions upon the relation between transpiration and the ash content of corn plants. 1913 and 1914 172
71. Relation of ash content to transpiration from corn plants grown in three degrees of soil moisture content, as affected by the atmospheric evaporating power of two different seasons. 1913 and 1914 173
72. Summary of ash ratios for dry and humid greenhouses, 1912, and for the two years, 1913 and 1914 174
73. Relation of ash content of Pride of the North corn plants to transpiration and fertility of soil. 1914 176
74. Relation of ash content of Pride of the North corn plants to transpiration and fertility of soil. 1913 and 1914 177
75. Relation of ash content of corn to transpiration and fertility of soil. (Average of three fertility tests.) 178
76. Relation of ash content of Hogue's Yellow Dent corn plants to transpiration and moisture content of soil. 1913 and 1914 179

TABLE PAGE
77. Summary showing relation of ash content of Hogue's Yellow Dent corn plants to transpiration and the moisture content of soil. Average for 1913 and 1914 180
78. Relation of ash content of corn plants to transpiration and size of potometers. 1914 181
79. Relation of ash content to transpiration, variety, and kind of crop. 1914 183
80. Summary of histological leaf measurements of corn and sorghums grown in the acclimatization and variety tests in potometers. 1914 185
81. Summary of relation of varying degrees of soil moisture and of manure to the number of stomata, growth, and water requirements of corn. 1914 186
82. Summary of relation of different degrees of soil fertility to number of stomata, growth, and water requirements of corn. 1914 187
83. Summary of stomatal and epidermal relationships 188

SUMMARY.

1. It is concluded from a general review of methods that the one best suited for studying the use of water by crops is to grow the plants to that stage of maturity at which they are normally harvested in farm practice, under control conditions in pots sufficiently large to grow a normal plant according to the fertility of the soil. This method, however, is, in general, subject to many sources of error, which must be overcome in order that reliable data of importance may be secured. Many investigations heretofore reported have been subject to vital errors. Means for the elimination of such errors are discussed.

2. The object of experiments reported in this bulletin has been to determine principles according to which water is used by crops. In many agricultural districts, water is frequently a seriously limiting factor in crop production. It has been thought that some means might be devised thru a correct understanding of the principles involved, whereby economy in the use of water in farm practice could be increased. In this effort there are two chief points of attack, namely, (1) adjusting the external factors to the needs of the plant, and (2) selecting plants adapted to the conditions.

3. Corn (*Zea mays*) has been used altogether in a study of the relation of environmental factors to the water requirement. In addition, several sorghums and sunflowers have been compared with corn, and a number of varieties of corn differing in acclimatization and plant characters were compared.

Single plants were grown in galvanized-iron pots filled with soil. With the exception of an experiment to determine the effect of the amount of soil and one small greenhouse test, all pots were 16 by 36 inches in size. The amount of soil contained varied slightly, according to soil type, and in different years, but their capacity was approximately 250 pounds of moisture-free soil.

The rain was excluded and evaporation from the soil surface reduced to an almost negligible amount. The quantity of water taken up from the soil and transpired by the plant was determined by the loss in weight of the entire pot in which the plant grew. Except in experiments to determine the effect of various degrees of relative saturation, an optimum supply of water was maintained practically constant. Except in a few greenhouse tests, all pots were situated in a cornfield with their top level with the surrounding land, so that the exposure of the plants was quite normal.

A comparison of plants grown in the potometers and in the field under normal conditions shows that the yield in the potometers was entirely normal.

4. The limitation of the amount of soil thru the size of the potometer may be a great source of error in pot experiments. It seriously affects not only the transpiration relationships but the entire development of the plant.

5. The soil in pots fully exposed to the sun acquired a somewhat higher temperature than normal field soil, but the water requirement per pound of dry matter was affected only slightly. It appears that comparable data may be secured from exposed pots.

6. Much variation exists in the results obtained from different pots receiving similar treatment. Error due to such individuality is greatly reduced by repetition.

7. The "probable error" has not been calculated for the results from these experiments, because it is evident in actual practice that knowing the "probable error" for such a small number of cases has little value.

8. Transpiration is essentially evaporation. The rate of water loss from a corn plant is affected in a rather similar manner by changing climatic conditions as it is from a physical free water surface.

9. The amount of water transpired from a given leaf-area of corn (based on expanse of leaf rather than both surfaces) is approximately one-third as great as the evaporation from a free water surface of the same area.

10. The maximum transpiration as well as the maximum evaporation rates occur between 1 and 3 p. m. Prior to this time the increase is gradual from early morning, and following it the rate gradually recedes until late in the evening. The rate of water loss follows the same general sequence as the diurnal climatic factors.

11. Transpiration is reduced relatively more during the night than is evaporation. This may be explained, perhaps, by the fact that the leaf stomata actually close almost completely at night, and as a result the opportunity for diffusion is reduced.

12. Variation in the water requirement from day to day is very marked. Occasionally this daily variation amounts to 300 or 400 per cent in successive days. The maximum variation observed in two successive days has been 600 per cent.

On days of extreme temperature in very dry years there may be an atmospheric demand of 10 pounds of water from a single average corn plant during 24 hours. The greater part of this exists for a period of about seven hours in the driest, hottest period of the day. Such days are exceptional, but they are very critical for corn in case there is not sufficient moisture in the soil to supply the demand. In a comparatively short time the corn may receive injuries from which it never fully recovers. Bearing this in mind it is evident that a period of brief duration may affect yields more than the annual amount of rainfall.

13. The amount of water used during each week of growth gradually increases until the plants have developed their maximum leaf-area. The four or five weeks following this are usually the hottest and driest of the season, and the transpiration rate remains high. Fully one-half of the total water used by the plant is transpired during this period of about five weeks. Following such a period, the transpiration falls off rather rapidly until maturity is reached. The rapid transpiration rate during the tasseling and earing period is coincident with this condition of the plant and not the result thereof.

14. A marked variation exists in the water requirement of different years, due to natural climatic differences. There is a rather consistent relationship in the relative seasonal variations between the (1) transpiration per unit of dry matter, (2) transpiration per unit of leaf-area, and (3) evaporation from a free water surface. There is no such thing as a definite water requirement which is constant for any one kind of crop.

15. As an average for three greenhouse tests conducted during two years, a difference of 22 per cent in relative humidity and 1.7° F. during the day caused a difference of 42 per cent in the water requirement per pound of dry matter, 38 per cent in the transpiration from a unit of leaf-area, and 46 per cent in the evaporation from a free water surface.

16. Corn plants which had been grown for two months in a greenhouse with humid atmosphere exhibited no different transpiration rate from a given leaf-area when transferred to a dry greenhouse than took place from plants which had been continuously grown under the dry conditions. The same is true of plants which were transferred from a dry to a humid greenhouse in comparison with plants continually grown in the humid atmosphere. There appears to have been no histological adaptation due to previous condition of growth which would affect the rate of transpiration when the plants were subjected to widely different climatic conditions.

17. Transpiration is found to exert a marked reduction in the leaf temperature when the air temperature is high, and as a result exercises a valuable self-protection against water loss.

A transpiring leaf was found to be uniformly cooler than a dead, dry one, amounting under the severe climatic conditions of a test in 1913 to 8.6° F. in the sun at 2 p. m. when transpiration was maximum and 4.2° F. in the shade at the same time. The transpiring leaf was 4.1° F. cooler in the sun and 3.2° F. cooler in the shade at 2 p. m. than was the air under similar conditions. It cannot, however, be concluded that it is an object of transpiration to prevent excessive heating of the leaves, but rather that this cooling is merely a fortunate coincidence.

18. As measured in terms of evaporation from free water surfaces at different elevations in corn, wheat, and oats fields, the vegetation is a great protection against excessive transpiration and also against evaporation from the soil surface.

19. A shallow free-water-surface evaporation jar containing only about 1.5 inches of water is very sensitive to climatic changes and responds more quickly than a deeper body of water.

20. A reduction in soil-moisture content below the optimum during three years reduced the water requirement per pound of ear corn 4.3 per cent, and per pound of total dry matter 7.9 per cent. This reduction in water requirement was, however, accompanied by 37.3 per cent reduced stalk yield, 28.5 per cent reduced yield of ear corn, and 30.7 per cent lower yield of total dry matter. It appears that it would be impracticable to lower the soil-moisture content intentionally below optimum for the sake of so slight a reduction in the water requirement, because yield is reduced relatively so much more.

An increase in the soil-moisture content above the optimum during three years, increased the water requirement per pound of ear corn 13.5 per cent, and per pound of total dry matter 8.2 per cent. This increase in water requirement was accompanied by 11.3 per cent reduced stalk yield, 21.1 per cent reduced yield of ear corn, and 16.7 per cent lower yield of total dry matter. The increased water requirement in the production of dry matter is not due to an effort on the part of the plant to get rid of surplus water or to greater ease in obtaining it, but rather to a less thrifty growth due to some detrimental effect from an overabundance of soil moisture, and consequent reduced available fertility.

21. The water requirement per pound of dry matter is much larger in an infertile soil than in a fertile soil. Increasing the fertility of the soil reduces the water requirement for grain production and for total dry matter. An application of manure has a much greater effect upon an infertile than upon a fertile soil. Thus, as an average for two years, equal applications of sheep manure to infertile, intermediate, and fertile soils reduced the water requirements for ear corn production 42.6 per cent, 25.4 per cent, and 10.5 per cent, respectively. For total dry matter

these water requirements were reduced 28.9 per cent, 17.1 per cent, and 8.1 per cent, respectively. However, the total water requirement per plant was increased by an application of manure to infertile, intermediate, and fertile soil respectively 106.7 per cent, 42.6 per cent, and 28.7 per cent. From these figures it is apparent that increasing the fertility does not reduce but rather greatly increases the total amount of water necessary per plant. This is due to increased plant growth. The reduction in water requirement per pound of dry matter is due, not to some effect of a denser soil solution upon the need for a rapid transpiration rate, but rather, simply to a more thrifty and vigorous growth of the plant, resulting from a more favorable supply of food materials. It appears to be more a matter of nutrition than of transpiration.

23. The average water requirement per pound of dry matter of two varieties of corn which had been grown for many years under the humid conditions of New York was approximately the same as the average for two varieties which have been grown continuously under the relatively dry conditions of western Nebraska.

24. The extreme variation in the water requirement of 11 different corns was 230 pounds and 296 pounds per pound of dry matter, which suggests that varieties may differ markedly in their water requirement. Most varieties, however, were rather uniform in this regard.

25. Several corns with alleged special drouth resistance possessed practically the same water requirements per pound of dry matter as the average for all 11 corns tested.

26. The water requirement for milo was the same as the average for 11 corn varieties, while it was considerably higher for Black Amber sorghum. It appears that the drouth-resistant qualities of certain crops must lie elsewhere than in a low water requirement per pound of dry matter.

27. Wild sunflowers possessed a water requirement per pound of dry matter approximately double that of corn, and a total water use somewhat greater than that of three corn plants.

28. A study was made of the intake of soil solutes as measured in terms of ash content in the crop harvested. Data were obtained concerning the relation between transpiration and ash content as affected by (1) atmospheric humidity, (2) seasonal climatic differences, (3) soil fertility, (4) soil moisture, (5) kind of crop and variety, and (6) limitation of the amount of soil thru the size of the potometer.

An increase in atmospheric humidity under greenhouse control, which lowered the free water evaporation 47 per cent, reduced the amount of water transpired per gram of ash content 38 per cent, and per gram of dry matter 40.5 per cent.

A natural climatic difference which lowered the free water surface evaporation 40 per cent during July and August in 1913, as compared with 1914, reduced the transpiration per gram of ash content 22 per cent and per gram of dry matter 27 per cent.

The greater the availability of the soil solutes in different degrees of soil fertility, other conditions being equal, (1) the greater was the amount of solute taken in per unit of water transpired, (2) the greater was the dry matter produced, (3) the greater was the total amount of water transpired, (4) the greater was the total amount of solute taken into the plant, and (5) the smaller was the amount of water used per unit of dry matter.

Less water was transpired per gram of ash content and also per gram of dry matter in a relatively low soil saturation than where an abundance of water was present.

The size of the potometer and consequent degree of soil limitation exerts a great influence upon the relation of transpiration to the intake of soil solutes. The quantity of transpiration per gram of ash content decreases rather consistently as the size of the potometer and amount of soil increases. In potometers containing 32.5, 85, 150, 239, 583, and 956 pounds of soil, the amount of transpiration per gram of ash content was: 6.14, 5.70, 5.20, 5.50, 5.07, and 4.32 kilograms, respectively.

Considerable variation exists in the ash and transpiration relationships of different corn varieties, but there appears to be no absolute correlation between the percentage of ash, the quantity of water transpired per gram of ash content, or the transpiration per gram of dry matter. There is, however, a strong tendency for varieties having a low water requirement per gram of dry matter, to have also a relatively low transpiration rate per gram of ash content. Milo and Black Amber sorghum transpired a slightly smaller quantity of water per gram of ash content than the average for the corn, while sunflowers transpired relatively much more per gram of ash content.

From a review of all of the data it may be concluded that at least within the practical limits of crop production, other things being equal, an increase in the density of the soil solution is accompanied by an increase in the amount of solute taken into the plant per unit of water transpired. Such a relationship is subject to climatic influences. Plants growing in a weak soil solution as exists in a soil of low fertility, under conditions of low evaporation, may take in a larger amount of solutes per unit of water transpired than would be the case in a stronger soil solution under conditions of high evaporation rate. The density of the soil solution as taken into the plant is not necessarily the same as the density of the soil solution as it exists within the soil. The transpiration rate may be independent of the density of the soil solution as it exists within the soil or as taken into the plant. The evidence in no way corroborates the theory that the necessity for or the rate of transpiration may be regulated thru the density of soil solution.

29. Considerable variation existed between the different varieties of corn and sorghum in regard to the thickness of the leaf and of the epidermis and also in the number of stomata per unit of leaf-area. There was, however, no apparent striking or consistent correlation between these histological coefficients and the transpiration rate per unit of dry matter or per unit of leaf-area of the different varieties. There was also no striking response in the relative number of stomata to variation in either soil moisture or soil fertility.

30. As an average for 11 varieties of corn, a plant having 949 square inches of leaf-area had 104,057,850 leaf stomata. The stomatal apertures in the epidermis of both sides of the leaf occupied, when open, 1.52 per cent of the entire area of the leaves. The stomata were found to be practically closed at night and also when the leaves are wilted. The entire epidermis comprised 30.8 per cent of the leaf thickness.

31. Many of the factors influencing the economy of water use by plants, which have been commonly regarded as directly influencing the transpiration rate as such, are rather factors in plant nutrition. Any factors which cause malnutrition result in a relatively high water requirement in the production of dry matter, because of the continued use of water without a normal increase in dry matter.

Transpiration appears to be a purely physical phenomenon, depending primarily upon the moisture supply in the leaf and the evaporating power of the atmosphere, which is modified in some degree by temperature effects resultant within the leaf from chemical activity, transpiration, and from the absorption of radiant energy.

TRANSPIRATION AS A FACTOR IN CROP PRODUCTION.

BY T. A. KIESSELBACH.

PART I. GENERAL SURVEY.

Such large quantities of water are used in the growth of agricultural crops that the water supply is frequently a limiting factor in production. The importance of proper water relationships has long been recognized, and the subject of transpiration is deserving of thoro investigation.

Water taken in by the roots of plants during growth either enters chemically into the products of photosynthesis or escapes from the above-ground parts of the plant (mainly the leaves) as the result of internal and external forces tending to establish an equilibrium. The relative amount entering into chemical combination is negligible.

The forms in which water escapes from the leaves may be classified as (1) water in liquid form and (2) water vapor. The former is negligible in amount and results occasionally from internal pressure caused by high turgesence, which forces drops of water thru minute water pores in the epidermis. The second source of water loss, namely, evaporation, practically equals the amount taken into the plant, and is caused by the evaporating power of the atmosphere adjacent to the leaf. A small amount is evaporated directly thru the nearly impervious walls of the epidermal cells.[1] The remainder is evaporated into the air spaces within the leaf from adjoining cells, and is removed thru the stomata in

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Acknowledgment for efficient assistance during the course of these experiments is made to Messrs. J. A. Ratcliff, C. A. Helm, F. D. Keim, R. E. Holland, Ernest Anderson, Bert Danley, E. R. Ewing, and Miss Bessie Noyes.

References to previous publications from this Station on the subject of transpiration are as follows: Montgomery (1910), Kiesselbach (1910), Kiesselbach and Montgomery (1911), and Montgomery and Kiesselbach (1912).

[1] Barnes (1910, p. 327) states that, "Of the total water lost, scarcely more than 20 per cent and as little as 3 per cent escapes thru the epidermis." Barnes does not state how this estimate was obtained. His estimate probably covers the extreme range of plants. With our cultivated crops this cuticular transpiration probably does not greatly exceed the lower limit.

the exchange of gases by diffusion which continually takes place with the exterior.

For practical purposes these two sources of water loss by evaporation (cuticular and stomatal) from the plant may be placed in one group, and for the sake of brevity and distinctiveness will be included in this bulletin under the old term "transpiration," altho there has been some contention in recent years that it should be called merely "evaporation from the plant."

CHARACTER OF PAST WORK.

Woodward (1699)[1] was apparently the first to measure this water loss. Stephen Hales conducted transpiration experiments as early as 1736, having in view a possible application to agriculture. Since then many experiments have been made both for purely scientific and for applied purposes.[2] Burgerstein had recorded 394 publications on transpiration in 1904, and the number has since been greatly increased. Few phases of the subject have been left uninvestigated. This, however, does not necessarily mean that the problems have been solved. On the contrary, that stage in the work has now been reached when we can look upon the past largely as preliminary, preparing the way for more significant experiments. This is not to be considered in the light of discredit to the earlier workers. Methods of observation have simply undergone a natural evolution. The results of many experiments have been rendered questionable by a full appreciation of the sources of error entering into them.

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[1] The year in parentheses following an author's name in the text serves to associate the reference with a particular publication in the bibliography (pp. 209), where the complete title is given.

[2] A number of investigators have reviewed more or less critically earlier work on the subject of transpiration.

(1) Abbe (1905) reviewed a number of experiments and speculated concerning their practical application.

(2) Burgerstein (1887, 1889, 1901, and 1904) assembled and discussed briefly all available publications concerning transpiration. In 1887, he reviewed chronologically 236 publications. In 1887 the general subject of transpiration was divided into subtopics, under which the work of investigators to date was discussed somewhat critically. Eight additional investigators were listed. In 1901, 109 additional publications were listed chronologically, and discussed according to general subtopics. The monograph published in 1904 contains a list of practically all transpiration studies prior to that date. Methods of investigation are reviewed in a critical attitude.

(3) Briggs and Shantz (1913 b). This publication reviews in a critical manner practically all the experiments in which rooted potted plants were grown beyond the seedling stage, relative to the use of water by plants in the production of dry matter. Experiments with seedlings were not considered because of the unreliability of the method. Both a summary of the results and a fairly complete statement of the methods used are given with each review.

(4) Montgomery (1912). Various methods of studying the water requirements of plants are outlined, and attention is called to the need for more uniform and accurate methods, so that the work of different investigators may be comparable.

(5) Eberdt (1889). This publication reviews experiments dealing with the relation of transpiration to certain atmospheric conditions, including light, humidity, temperature, wind, and the effect of jarring.

(6) Many of the investigators cited in the bibliography on pages 209 to 214 give partial reviews of previous experiments, and include more or less extensive bibliographies. Many investigators not referred to in this bulletin have also published excellent bibliographies.

The factors influencing transpiration determinations may be grouped into two great classes: (1) Factors influencing transpiration determinations as sources of experimental error, and (2) factors influencing transpiration in fact. The significance of the results of the numerous investigations which have been published depends upon the reliability of the methods by which they were obtained.

OUTLINE OF METHOD PRINCIPLES FOR STUDYING TRANSPIRATION.

The general principles involved in the various methods of observation may be outlined as follows:

I. Basis of comparison.
    1. Total transpiration per plant.
    2. Transpiration per unit of leaf-area.
    3. Transpiration per unit of weight. (Green or dry weight.)
        a. Weight of grain.
        b. Total weight minus roots.
        c. Total weight including roots.

II. Manner of determining the transpiration.
    1. Demonstrative.
        a. Cobalt method.
    2. Quantitative.
        a. Field estimates.
        b. Collecting and measuring the water transpired.
        c. The potometer method.
            1¹. Type.
                a¹. Measuring the intake of water.
                b¹. Determining the amount transpired by loss in weight.
            2¹. Character of plant.
                a¹. Cuttings.
                b¹. Seedlings.
                c¹. Mature or intermediate stages.

A number of very ingenious and in some cases intricate modifications and combinations of the methods outlined have been devised. However, the principles involved are the vital part, and for these the outline is inclusive.

BASIS OF COMPARISON.

(1) Comparing transpiration rates solely by total water loss per plant is of significance only in special cases. During short periods in which the leaf-area and thrift of the plant are practically constant, the effect of variations in environmental factors on the total water requirement for a unit of time may be noted. To know the total amount of water used in the normal growth of a plant is also of value in calculating the approximate amount of water required for a unit of field area of a similar crop, provided growth conditions are comparable. The relative total transpiration cannot be regarded as an index of relative growth.

(2) Certain interrelationships between the plant and its atmospheric environment may be studied by basing the relative transpiration rates upon a unit of leaf-area. The effect of difference in leaf structure and condition of leaf may also be observed by the water loss from a unit of leaf-area.

(3) From an economic standpoint the most important basis for comparison is the amount of water transpired in the production of a unit of dry matter. To obtain these data it is requisite that the total yield of crop and the total water consumption be secured, which data furnish a basis for making all important deductions in which the yield of dry matter is concerned.

The total water transpired, the amount of water used per unit of dry matter, and the amount per unit of leaf-area bear no necessary relation to one another. The relative effect of soil differences has very frequently been measured solely in terms of total loss per plant or loss per unit of leaf-area during only a fraction of the lifetime of the plant. Since no necessary relation exists between these characters and the addition of dry matter in the plant, the data are inapplicable and are of little importance.

METHODS OF DETERMINING TRANSPIRATION.

THE COBALT METHOD.

The methods which have been employed may be grouped first according to whether they are largely demonstrative, or whether quantitative measurements of water loss may be made. The cobalt test is a case of the former, in which a blue sheet of cobalt paper held in close contact with the transpiring surface loses its color from the effect of moisture. Paper infiltrated with certain other chemicals than cobalt chloride may also be used. Since the rate of change in color depends upon the rate of water application to the paper, it is possible to make a somewhat relative comparison of the rate of water loss from two leaves, but it is impossible to make an accurate quantitative measurement.

Livingston (1912, pp. 121-123) describes a standardized cobalt test and suggests that it "should be of value in many problems of physiological ecology and of agriculture. The study, for example, of the relative drouth-resisting powers of different varieties, an important one in agriculture, should be much facilitated by these means."

In a later paper (1913), "The Resistance Offered by Leaves to Transpirational Water Loss," Livingston[1] gives tables and charts comparing hourly records from the standardized cobalt test with evaporation from white and brown atmometers, and with actual "relative" transpiration from plants. It is evident that the hygrometric paper gives only approximate comparisons and cannot be considered quantitatively reliable. The method is wrong in principle for determining the plant response to normal climatic conditions. That portion of a leaf covered by an opaque paper held in close contact with it by means of a glass plate fastened with clamps for 10 minutes or longer certainly is not exposed normally to the surrounding atmosphere. The same may be said of the water bottle with which it is compared. It would be impossible to prevent the relative temperatures and other conditions of the leaf and water bottle from fluctuating during the reading, which destroys the possibility of standardization.

FIELD ESTIMATES.

Field estimates[2] of the amount of water used by plants are based upon initial and final soil-moisture samplings together with rainfall records during the period between moisture determinations. Since no accurate estimate can be made of the run-off or evaporation of moisture from the soil, results secured cannot be regarded as indicating the amount of transpiration.

COLLECTION OF TRANSPIRED WATER.[3]

The method of collecting and weighing the transpired water has been used rather extensively. Some closed vessel containing an absorbent salt is used, and a leaf or twig of a growing plant is inserted into it. A number of intricate and ingenious modifications have been devised. The increased weight of the salt indicates the amount of transpiration from a given area. This method would appear to be fundamentally wrong in that the leaves inclosed are not subjected to the same climatic influences as the main portion of the plant tested and consequently will not be representative of the transpiration taking place from the plant.

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[1] Other investigators who have used a cobalt or similar test are Stahl (1894, pp. 117-145) and Merget (1878, p. 293).

[2] This method has been used by the following investigators, some of whom realized its limitations: Briggs and Shantz (1913), Leather (1911), Powers (1914), Widtsoe (1912), and Willard and Humbert (1913).

[3] This method has been used in recent years by Shreve (1914), Roberts and Freeman (1908), and Cannon (1905).

A slight difference in the climatic factors may have a marked effect upon the transpiration rate. If the method were reliable, it would be of value in measuring transpiration from plants rooted in their natural habitat, and which cannot be transferred to pots for weighing.

THE POTOMETER METHOD.

The potometer method consists in the use of a vessel filled with water, nutrient solution, sand culture, or soil, by which the amount of transpiration is determined from contained cuttings or rooted plants, either by loss in weight or by measuring the intake of water.

MEASURING THE INTAKE OF WATER.

Early investigators determined the transpiration extensively by measuring the amount removed from the containing vessel. The base of a cutting or seedling would be inserted in a sealed bottle filled with water or nutrient solution, and having a graduated capillary tube by means of which the loss could be read in cubic millimeters. The method also had strong opponents who declared that the intake of water could not be a measure of the outgo from the plant. They were justified in that the water content of the plant varies at times according to turgescence, and more water may be taken in than is transpired, or somewhat more may be transpired than is taken in. Such a discrepancy is, however, only serious when the total losses are very small and for only very short intervals—as was customary with this method. Error due to variations in the amount of water contained by the plant caused by differences in turgidity would, in general, be negligible in its effect upon the total amount of water transpired in growing to maturity.

LOSS IN WEIGHT.

Determining transpiration by loss in weight of the potometer with its contained plant is correct in principle, and, when healthy rooted plants are used, most nearly approaches natural conditions. If the necessary precautions are taken, it registers quite accurately the amount of transpiration under the conditions of the test. When the experiment extends over any great length of time, it is necessary to measure the water applied during growth as well as the difference in initial and final moisture content of the soil. A number of self-recording arrangements have been devised for securing a continuous record of water loss. These are, however, not essential.

CHARACTER OF PLANT.

Quantitative measurements with potometers may be divided into two general groups, according to whether plant cuttings or rooted plants are used. Rooted plants are much to be preferred and in fact are indispensable for a serious study of transpiration. We cannot rely upon conclusions drawn from other than normally functioning plants, unless the object is to study the abnormal condition as such.

Plant Cuttings.—The great source of error with the use of cuttings is that the entrance of solutions does not take place in a normal manner. The tests must also be of short duration and under protected conditions, so that the rate of water loss is sufficiently suppressed for the stem to take in the moisture as quickly as it is lost from the leaves. Especially in experiments correlating transpiration and the production of dry matter, it is essential to use rooted plants functioning in their normal manner under the environmental conditions of the test.

Rooted Plants.[1]—Investigations with rooted plants may be grouped according to the stage of maturity upon which results are based. They fall naturally into three main classes, viz: Seedlings, mature plants, and intermediate developments. Briggs and Shantz (1913 b) pointed out the chief source of error from the use of seedlings when transpiration is correlated with dry matter, and they have eliminated such experiments from serious consideration. We are in hearty accord with them and believe that important conclusions relative to dry weight cannot be drawn from seedlings. Sufficient growth must be made to overcome the effects of mere translocation of substance from the seed. This stage may be reached long before the plants are mature, but with few exceptions, in the case of certain agricultural crops, the water requirement should doubtless be determined up to that stage at which they are commonly harvested in farm practice. It has been observed that the relative effect of two treatments on the early growth of plants is sometimes very different in degree from the final comparative growth at maturity.

It is entirely possible to establish certain interrelationships between transpiration and atmospheric conditions by the use of small plants, even in the seedling stage. However, these are limited because of the rapid change in the size of the plants and must, with a few exceptions, be regarded more as demonstrative than as quantitative measurements.

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[1] A list of investigators who determined transpiration from plants grown beyond the seedling stage by loss in weight of the potometers is given on page 36.

SUMMARY OF DISCUSSION ON METHOD PRINCIPLES.

In summarizing the discussion of the principles involved in the various methods which have been used for quantitative transpiration determinations, it is concluded that the use of potometers with rooted plants alone can be relied upon to furnish significant results. Plants grown beyond the seedling stage are indispensable when the relative transpiration is based upon the production of dry matter. This basis of comparison is of chief interest from an applied agricultural standpoint. However, certain principles of response to variable conditions can be satisfactorily determined by the loss per unit of leaf-area and the total loss per plant during a given length of time.

DETERMINING THE TRANSPIRATION OF FIELD CROPS.

To determine the relation of transpiration to production it is necessary to secure the ratio of water loss to total dry matter produced, and in the case of grain crops also to the yield of grain. To attempt any quantitative application to field conditions it is desirable also to know the total water transpired per plant, the total yield of dry matter per plant, and the normality of growth. In comparisons of different kinds of crops these must also be grown under conditions comparable to the field conditions of the particular crop tested.

To determine merely the relative effects of two differing factors, such as soil moisture, soil fertility, or relative atmospheric humidity, it is not so essential to have the plants exposed to normal field climatic conditions. It is very desirable, however, to have as complete a record as possible of all environmental factors which may influence the transpiration rate.

SOURCES OF ERROR IN POTOMETER TESTS.

The potometer method in which growing rooted plants are grown beyond the seedling stage is correct in principle for studying the water requirements of crops. This method is itself, however, subject to sources of error, many of which must be eliminated in most part in order to secure significant and applicable results. Since we must rely upon this method for securing transpiration data as related to the yield of agricultural crops, and since nearly all such data of importance have been secured by this method in the past, it becomes desirable to consider the special sources of error entering into it. Such a knowledge is necessary to evaluate correctly the results of an investigation. The following outline is suggestive of these sources of error.

OUTLINE OF FACTORS INFLUENCING TRANSPIRATION DETERMINATIONS WITH ROOTED PLANTS IN POTS AS SOURCES OF EXPERIMENTAL ERROR.

1. Character of potometer and contents.
    a. Limitation of amount of soil—
        1. Thru size of potometer.
        2. Thru number of plants grown in potometer.
    b. Limitation of fertility of soil.
    c. Improper distribution of soil moisture.
    d. Evaporation from surface of soil.
    e. Entrance of rain water.
    f. Exposure of potometer and consequent effect on soil temperature.
    g. Unintentional lack of uniformity in soil.
2. Environment.
    a. Testing under unnatural habitat.
3. The plant.
    a. Plant individuality.
        1. Insufficient number of replications.
        2. Disease and injury.
    b. Stage of maturity.
        1. Insufficient development.
4. Errors due to methods of computation.
5. The personal element in drawing conclusions.

DISCUSSION OF SOURCES OF ERROR IN POTOMETER TESTS.

CHARACTER OF POTOMETER AND CONTENTS.

One of the most common sources of error in determining the amount of water transpired in crop production is the unintentional undernourishment of the plants, either thru the use of too small a potometer or thru growing too many plants in a potometer. Hellriegel (1883), Leather (1911), and Briggs and Shantz (1913a and 1914) conclude that the amount of water transpired per unit of dry matter produced is increased by a deficiency in the supply of food materials, which may become a source of experimental error. The same conclusion may be drawn from experiments reported in this bulletin. Below a certain range of optimum fertility, the plant makes a poorer growth, and the water requirement ratio is increased as the condition is extended in the adverse direction. This is especially true in relation to grain production.

Consequently, the amount of soil available for each plant should be sufficient to enable it to make a normal growth typical of field development. If the object is to determine the need for fertilizer applications to a particular soil, care must be exercised that the amount of soil rather than its degree of fertility is not the limiting factor. It appears that any soil, no matter how fertile, will respond favorably to fertilizer application if overcropped.

In determining the water requirement ratios of different crops it is important that the relative number of plants of each crop grown in a potometer should bear approximately the same proportion to one another as are grown under field conditions. Thus, in eastern Nebraska we grow in the field 100 wheat plants upon an area of land equal to that occupied by one corn plant. Consequently in comparing wheat and corn in pots we should grow 100 plants of wheat in a potometer of the same size as we use to grow one corn plant. Investigations have shown that plants adjust themselves to a certain extent, and the stand may vary somewhat without materially affecting results.

By such an adjustment of the relative number of plants per pot, the amount of soil, if it becomes a limiting factor in the growth of one crop, does so proportionately with the others as well. Investigators generally have failed to provide against both overcropping the soil and lack of reasonable uniformity in the degree of cropping, in comparing different crops. Thus, Leather (1910, 1911) grew three to four plants each of 14 different kinds of crops, including wheat, barley, oats, linseed, sarson, peas, gram, maize, juar, rice, murwa, kodo, rahar, and guar in quantities of soil ranging from 14 to 50 kilograms. Pots of uniform size were used in each experiment, except where the object of the test was to compare the effect of potometers of different size. In Leather's experiments a corn plant was given from 3.5 to 12 kilograms of soil according to the size of potometer, while wheat, oats, and the other plants were given the same amount. His plants were grown to maturity. It is very evident from the yields and the photographs that the quantity of soil was altogether too small for corn and several other crops, while it was much more nearly optimum for small grains. Leather also investigated the fertilizer requirements of the soil in these small pots and their effect upon the water requirements per pound of dry matter. With such a relatively limited quantity of soil, neither a satisfactory crop test nor fertilizer test could be made.

Briggs and Shantz have tested 20 kinds of crops, consisting of more than 100 varieties at Akron, Colorado, and also a number of varieties in other localities. Regarding the number of plants in a potometer, these investigators state (1913, p. 10) that 20 small-grain, 8 sorghum, 6 corn, and 6 sugar beet plants were grown. The potometers all contained 115 kilograms of soil. This provides approximately the same amount of soil for three small-grain plants as for one corn plant. Under eastern Colorado farm conditions approximately 50 seeds of wheat are planted on an area of land equal to that occupied by one corn plant.

Speaking in a general way, it may be concluded that Briggs and Shantz grew six corn plants in a potometer where they should have grown one, and in proportion to corn they grew 20 wheat plants when they should have grown 300.

Altho Briggs and Shantz were of the opinion that cans of the size used by them were of adequate size to allow normal development of the plants, it appears from their illustrations and tables that at least the corn and grain sorghums were very much underdeveloped, the corn more so than the sorghums, however. The total yield per potometer of dry matter from the six corn plants is about equal to what the yield from one plant of the larger varieties should have been.

Briggs and Shantz (1913a, p. 18; 1914, p. 5) concluded from tests with Kubanka wheat in 1911 and 1912 that the soil used by them bore sufficient fertility for normal development. The fertilizer application increased the actual yield of dry matter 9 per cent in 1911 and reduced it 3 per cent in 1912. In 1911 the water requirement of the unfertilized set was 6 per cent above the fertilized set, and in 1912 it was 4 per cent below that of the fertilized set. While these tests show little need for fertilizer on the part of the wheat, they do not indicate what would have been the result on corn planted at a relatively much thicker rate.

The effect of overcropping upon the water requirement per unit of dry matter is much less marked than the effect upon the amount of dry matter itself. (See Table 4 of this bulletin.) This general problem of adjusting the number of plants to be grown in a unit mass of soil needs further investigation.

LIMITATION OF SOIL FERTILITY.

In certain lines of investigation the degree of soil fertility may become an important source of error. The principle is again involved that the ratio of water loss to dry matter is increased as the soil fertility is decreased below a normal range. In an experiment to determine the relative water requirements as related to the difference in climate of two distinct regions of the country, it is essential to use soils of equal productivity in both regions.

Otherwise, the difference in water requirements may be partly due to the difference in soil fertility. Thus, Briggs and Shantz (1913, Bul. 285, p. 61) compare the water requirements of both wheat and sorghum in Colorado and Texas during 1910 and 1911. Native soil was used in the tests, which may account for part of the difference assigned to climate. Briggs and Shantz recognize this factor in 1913 (Bul. 284, p. 15).

King (1905) compared the water requirements of corn in four States, using native soil in each case. No data are given by which we can estimate what portion of the difference in the several States is due to difference in soil fertility. Such comparisons give the combined effect of difference in soil and climate.

The need for similar precautions regarding uniformity of soil fertility applies to determining the variation in water requirement from year to year as well. Variation in soil fertility may influence the water requirement fully as much as climate.

IMPROPER DISTRIBUTION OF SOIL MOISTURE.

In experiments to determine the effect of variation in soil-moisture content, some investigators have added all the water either from above or from below. In those potometers having a low relative soil saturation, water added to a single portion may not become distributed thruout the soil mass, which will unintentionally affect the degree of saturation in the different parts.

EVAPORATION FROM SURFACE OF SOIL.

Of the forty-odd experimenters who have studied the water requirements for the production of dry matter with plants beyond the seedling stage, only eight have taken the necessary precaution to reduce the evaporation from the soil surface to a negligible quantity. Many have attempted to correct such loss by subtracting the water loss of similar uncropped pots from the combined evaporation and transpiration of cropped pots. The rate of surface evaporation is, however, affected by so many factors that not much faith can be placed in the accuracy of the method. The evaporation rate varies with the relative soil saturation, the soil texture, and the shading, which are certain to be variable factors between cropped and uncropped pots as well as between pots intended to be similar. In some experiments conducted in this manner, the amount of water transpired by the crop is so much larger than the amount evaporated from the soil that the experiment may indicate the character of the effect altho not in definite degree. We cannot assume that such experiments furnish dependable quantitative measurements.

Some investigators have made the error of assuming that the transpiration from the crop plus the evaporation from the soil surface in a pot represented a similar combined loss under field conditions and have called it transpiration plus evaporation. The amount of evaporation varies naturally in addition to the before-mentioned factors, with the amount of surface exposed, which has seldom been comparable with the area occupied by a similar amount of crop under field conditions.

ENTRANCE OF RAINFALL.

Most investigators of water requirements of crops have avoided the entrance of rain into the potometers. Part of the experiments have been conducted in greenhouses; part have been arranged to be moved under shelter in time of rain; while still others, which were fully exposed in the open, have been corrected for rain by keeping a record of the rainfall and adding the weight of the known depth and area of water to the amount lost in growing the crop. Very few have sealed the potometers so as to exclude the rain and yet permit continual standing in the open.

The greatest error from rain would result from sealing the entire surface except a small opening for the plant and assuming that this would keep out the rain. Our tests have shown that the plant acts as a funnel, and for each inch of rainfall 6½ pounds of water were caught by the leaves and conducted down the outside of a full-grown, well-developed cornstalk into the potometer. This would make an error of 65 pounds per corn plant, if 10 inches of rain should fall after it had made much growth.

EXPOSURE OF POTOMETER TO ATMOSPHERE.

In most transpiration experiments the potometer has been left exposed to the atmosphere, which results in soil temperatures somewhat different from normal field soil. The effect of such difference in soil temperature due to exposure is slight, at least within reasonable limits as indicated in Table 9 of this bulletin, and data obtained from the use of exposed potometers should be comparable and not far from normal.

UNINTENTIONAL LACK OF UNIFORMITY IN THE SOIL.

An unintentional lack of uniformity in the soil is not likely to arise frequently. It is perhaps best illustrated by Widtsoe's (1909, p. 5) fertilizer experiment in 1908 with four different types of soil. Pots filled with soil were used which had been left undisturbed since 1905, previous to which time the same soil contents had been subjected to varied treatments. Widtsoe assumed that the effects of different treatments in earlier years had been obliterated by the lapse of time, but such an assumption is not warranted.

A deterioration of soil-growing conditions may occur from confinement for a period of years in pots, as described in this bulletin, pages 157 to 159.

ENVIRONMENT.

Experiments have shown that the intensity of the various climatic factors bears a close relation to the water requirement. Consequently, results obtained under abnormal exposure should not be construed to give correct measurements for field conditions. To illustrate, Briggs and Shantz (1914) found that 10 per cent more water is used by Kubanka wheat fully exposed in an isolated place than is used by wheat sunk in a pit level with the ground in a wheat field. Again, the fully-exposed wheat transpired relatively 20 per cent more than wheat in a screened inclosure. Since the majority of the crop tests made by Briggs and Shantz (1914, p. 3) were made in this screened inclosure, they state that the "inclosure measurements, at least in the case of wheat, are less than 10 per cent below the water requirement of plants exposed under field conditions." In this way we are given a basis for correction in reducing to field requirements. The authors state (1913 a, p. 13) that "the determination of the relative water requirement of the different crop plants is, however, the main problem from an economic standpoint." It would be of great interest to know just how much the various crops differ under field conditions in their self-protection against evaporation influences. It seems probable that the leaves in a pumpkin field are differently exposed to the action of the wind and other climatic influences than are the plants in a corn or sorghum field. Again, it appears that the dense vegetation in an alfalfa meadow would provide greater self-protection against transpiration than the more open vegetation of a cornfield. This factor of difference in self-protection against evaporation is overlooked when crops are brought together out of their normal field conditions and are tested under one uniform abnormal exposure. It seems that we must consider the results in regard to the relative water requirements of different kinds of crops obtained in this uniformly exposed manner as doubtful until the relative degree of self-protection has been determined for each or a similar type of crop.

THE PLANT.

Plant individuality may be an important source of error in pot tests. The most practical way of overcoming this is by replication, which is quite effective as shown in Tables 13 to 21 of this bulletin. The plants may be replicated either within a pot or in different pots. In the former case, care must be taken not to introduce the additional error of overcropping and accidental or unintentional lack of uniformity in cropping.

Among the investigators who have made extensive tests, Briggs and Shantz have uniformly replicated their potometers in a given year more than other investigators, usually averaging together six similarly treated pots. The Nebraska potometers have all been replicated from four to eight times barring an occasional injured plant, with four as the standard number. Occasionally, potometers contain broken or diseased plants and should be discarded in compiling averages.

STAGE OF MATURITY.

This factor has been discussed as a source of error in connection with methods on page 25 of this bulletin. It was concluded that results with seedling plants are not dependable. The total water requirement up to the normal time for harvesting as a crop is of greatest practical interest. This requires mature plants with grain crops. In potometers too small to grow the crop normally to maturity, it should be harvested at a stage before the amount of soil has become an abnormal limiting factor.

Conclusive experiments have not been made to show the relative water requirement at different stages of maturity. Fest (1908), Von Seelhorst (1908, 1910), and Thom (1913) have investigated the effect on water requirement of harvesting at different stages, but have not discriminated as to what part of the difference in water requirement is due to climatic differences and what part to the stage of development.

ERRORS DUE TO METHODS OF COMPUTATION.

A rather common error in compiling data which results in incomparable summaries and wrong conclusions is the placing in an average column the averages for different crops or treatments which do not cover the same period of years. As an illustration, the following table has been compiled from King's reports.

Four-year summary of the water requirements of crops as given by King (1895, page 248). In addition, data are included to show the number of pots used and the years in which each crop was grown.

Four-year summary as given by King (1895)					Compilation from four annual reports to show how King's summary was obtained				
					Number of pots used				
Crop	No. of trials	Water per pound of dry matter	Dry matter per acre	Acre inches of water per ton of dry matter	1891	1892	1893	1894	Total
		Pounds	*Pounds*	*Inches*					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Dent corn.....	4	309.84	19,515	2.64	2	2	....	....	4
Flint corn.....	4	233.90	25,099	2.14	....	....	4	....	4
Red clover[1]....	3	452.80	9,613	4.03	....	2	....	....	2
Barley[2].......	3	392.89	10,819	3.43	2	2	....	....	4
Oats[3].........	5	557.34	10,755	5.02	2	2	....	4	8
Field peas.....	1[4]	477.37	8,017	4.21	....	2	....	....	2
Potatoes......	2	422.70	12,805	3.73	....	....	....	2	2

[1] King gives three pots, but the writer can find data for only two, tested in 1892, with the following results: 2; 564.4; 12,486; 4.76.

[2] Apparently should read: Barley 4; 388; 10,819; 3.39.

[3] Apparently should read: Oats 8; 553.3; 10,197; 4.92.

[4] Apparently should be two pots tested.

The data in columns 2, 3, 4, and 5 are given in this same form by King (1895) to show the relative water requirements of crops in Wisconsin. The other columns have been compiled to show how subject to error such a summary may be. King compares without qualification the water requirements of dent corn and barley tested during two years, 1891 and 1892, with red clover[1] and field peas tested one year, 1892; with flint corn tested in 1893; with oats tested in 1891, 1892, and 1894; and with potatoes tested in 1894. Such a summary is meaningless.

Briggs and Shantz (1914) have largely overcome this error in their comparison of the water requirements of crops tested during three years at Akron, Colorado, by arbitrarily increasing the ratios for 1912 30 per cent. Certain crops had been tested all three years, while certain others only two or one year. The crops grown continuously showed practically the same water requirements in 1911 and 1913, while the water requirement was approximately 30 per cent lower in 1912.

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[1] King apparently tested clover for two years, but the writer can find the records for only one year, 1892.

Widtsoe (1909) has been inconsistent in making a similar error of averages in tests where the effects of different soils and treatments have been averaged for four years. Data secured during one, two, three, or four years are given equal rating in comparing one with the other, and this error occurs in his Tables 6, 7, 8, 15, 20, 21, 27, 28, and 30, while it is partially or wholly recognized and overcome in Tables 5 and 24.

An error of averages may be made in averaging the water requirements in the production of grain and of total dry matter. Some potometers may fail to produce grain. For the purpose of comparing the relative water requirements for grain and for total dry matter in a certain crop, it is important that the same potometers be averaged in both cases. If certain potometers fail to produce grain, this should be charged against the average. If only four or five potometers out of six duplicates produce grain, the total of these four or five should be divided by the full number of potometers, or six. Briggs and Shantz (1914, Tables 6, 7, 13, 14, and 24) may be cited as examples of this error. An illustration of the point in question may be found on page 60, Table 4, column 3 of this bulletin. Three out of four duplicate small potometers failed to produce an ear. This lack of ear development due to shortage of available nutrients must be charged against the small potometers, and the weight of the one small ear produced must be divided by four to secure the average performance.

In the table which follows is given a list of the investigators to date who have based the transpiration requirement upon crop yield and used plants grown in potometers beyond the seedling stage. Data concerning a number of factors are also tabulated to show the lack of uniformity, and also the opportunity for error from a number of sources. A few of the investigators did not conform entirely in all of their investigations to methods credited to them in the outline. The publications of some also fail to give full information concerning part of the factors.

List of investigators who have studied transpiration in relation to crop yield, based upon plants grown beyond the seedling stage. [All water requirements were based on dry matter except those of Wilms (1899).]

Author	Year of publication	Size of potometer (Centimeters)	Weight of soil or sand (Kilograms)	No. potos. av.	Number of plants and crop per potometer	Stage of maturity	Approx. range in wt. of crop. (Grams)	Surface evaporation		Rain		Location
								Prevented?	Corrected?	Excluded?	Corrected?	
Briggs, L. J., and Shantz, H. L.	1913,'14 1915	41x61	115	6	6 corn, 8 sorghum 20 wheat[2]	Ripe	5.9-359	Yes	.....	Yes	.....	Screened inclos.
Daszewski, A. von[3]	1900	25x33	17.2	2	Potatoes	Ripe	36-380	No	No	Yes	.....	Outdoors
Deherain, P. P.[4]	1892	*	60.0	1	Clover, ray-grass	Ripe	39-99	No	No	......	.....	Field
Fest Franz	1908	*	17.3	*	5 beans	Vari'bl	255-681	No	Yes	Yes	.....	Greenhouse
Fittbogen, J	1873,'74	*x21	2.5-5	4	1 to 3 oats	Ripe	1.2-15.8	Yes	.....	Yes	.....	Outdoors
Fortier, Samuel	1903	43x76	*	1	19 oats	Ripe	56-311	No	No	Yes	.....	Field
Hasselbring, Heinrich	1914	30.5x38	30	6	1 tobacco	Norm.	188	No	Yes	Yes	.....	Field
Heinrich, Reinhold	1894	*	3 solution[5]	10	3 oats	Ripe	1.8-13.4	No	Yes	Yes	.....	Indoors
Hellriegel, F. H	1883	*x34-*x67	3, 4, 6,12,18	1-2	Seven crops	1-4mo.	.7-57	After 1870	Yes	Yes	....	Greenhouse
Harris, F. S	1914	*	7.7	2-6	12 wheat	Ripe	15-112	Yes	Yes	Yes	.....	Greenhouse
Il'enkov, P. A	1865	Flowerpots	*	1	1 buckwheat	Ripe	.39-14	No	No	Yes	.....	Lab. window
Kiesselbach, T. A	1910	25x30	16	4-5	1 corn	Silking	47-114	Yes	.....	Yes	.....	Field
Kiesselbach, T. A., and Montgomery, E. G.	1911	41x91	120	4	1 corn	Ripe	111-484	Yes	.....	Yes	Yes	Field
King, F. H	1892	189-liter barrel	*	2	4 corn, barley, oats	Ripe	199-450	No	No	No	Yes	Field
	1893,'94 '95	46x102	*	2	2 corn, 2 clover, 2 potatoes[6]	Ripe	138-639	No	No	No	Yes	Field
	1905	122x122	*	1	10 corn	Ripe	2,043-9,420	No	No	No	Yes	Field
Khankhoje, P	1914	*	11.3	1-3	3 wheat, 3 oats	Ripe[7]	1-40	Yes	.....	Yes	.....	Greenhouse
Kolkunov, V	1905	*	4.2	2	5 wheat, 5 oats, 5 millet	Unripe	*	No	Yes	*	.....	*
Lawes, J. B	1850	23x36	19.0	1	3 wheat, 3 barley, 1 pea, 1 bean, 1 clover	Ripe	6-35	Yes	.....	Yes	.....	Outdoors
Leather, J. W	1910,'11	23x30-30x56	12-50	1-2	3-4 14 crops[8]	Ripe	5-268	No	Yes	Yes	.....	Screened shelter
Liebscher, George	1895	*	9.2-11.7	3	Oats	Flower	32-139	No	*	*[9]	.....	Not stated
Maercker, Max	1896	*	6	1	Mustard	*	9-26	No	No	Yes	.....	Indoors
Marie-Davy, E. H.[10]	1874,	*	2	1	5 wheat	Ripe	2.3-9.7	No	No	Yes	.....	Outdoors
	1874,'75 '76	100x100	*	1	162 wheat	Ripe	187-479	No	No	Yes	Yes	Outdoors
Montgomery, E. G	1911	41x91, 76x91	114 and 454	4	1 and 2 corn	Ripe	433-580	Yes	.....	P'rtly	.....	Field

Montgomery, E. G., and Kiesselbach, T. A.	1912	41x91	105-143	4	1 corn	Ripe	113-472	Yes	.....	Yes	.....	Field
	1912	41x91	114	4	2 corn	Silking	167-215	Yes	.....	Yes	.....	Greenhouse
Ohlmer, W.	1908	25x33	17	4	5 wheat	Ripe	18-131	No	No	Yes	.....	Culture house
Pfeiffer, Theodor, et al.[11]	1912	*	18	4	24 oats	Ripe	8.5-116	No	Yes	Yes	.....	Outdoors
Preul, Franz	1908	25x33	20.5	4	9 wheat	Ripe	*	No	Yes	*	.....	*
Schroeder, M. R.	1896	*	5	1	4 barley	70-113 days	3.5-38	Yes	.....	Yes[12]	.....	Outdoors
Seelhorst, Conrad von[13]	1899	*	20	2	8 oats	Milk	38.5-55.2	No	No	Yes	.....	....
	1906	100x133	2400	1-3	20 rye, 30 wheat, 4 potatoes	Ripe	189-1,172	No	Yes	No	Yes	Outdoors
	1908	100x133	2400	1	Rye, barley, turnips	Ripe	823-883	No	Yes	No	Yes	Outdoors
	1908a	100x133	2400	1	Rye, potatoes, barley, lupine	Ripe	193-461	No	Yes	No	Yes	Outdoors
	1910	100x133	2400	1	Pasture and meadow mixture	Norm.	542-972	No	No	No	Yes	Outdoors
	1910a	100x133	2400	1	Rye	Ripe	339-526	No	No	No	Yes	Outdoors
Seelhorst, C. von, and Bunger, J.	1907	*	12	*	1-5 spring wheat	Ripe	10-76	*	*	*	*	*
Seelhorst, C. von, and Müther	1905	100x133	2400	1	Oats, clover	Ripe	655-1,096	No	Yes	No	Yes	Outdoors
Sleskin, P.	1908	8x15x16	420	1	3 sugar beets	Ripe	4.79	No	Yes	Yes	.....	Outdoors
Sorauer, Paul	1880	*	*	4-7	1 vitus and 1 phaseolus[14]	1-3mo.	1.7-10	*	*	Yes	.....	Greenhouse
	1883	*	1.7	4	1 rye, 1 wheat, 1 barley, 1 oats	39-60 days	.06-.7	*	*	Yes	.....	Outdoors
Thom, C. C.	1913,'14	61x91	*	2	Eighteen different crops	Ripe	*	P'rtly	*	*	*	Field
Widtsoe, J. A.	1909	61x76	*	1	Corn,[15] wheat, beets, peas	Ripe	29-730	No	Yes	Yes	.....	Outdoors
Widtsoe, J. A., and Merrill, L. A.	1892	61x76	*	2	Wheat, corn, peas, beets, lucern	Ripe	80-277	No	Yes	*	*	Outdoors
Wimmer, G.	1908	20x33	6.7	2-3	Chicory, ray-grass beets, carrots	Norm.	21-113 days	No	No	Yes	.....	Outdoors
Wilms, Johann[16]	1899	25x33	17.2	2	Potatoes	Ripe	36-380	No	No	Yes	.....	Outdoors
Wilfarth and Wimmer	1902	15x20-26x30	2.5-6.7	2	1 potato, 2 tobacco, 3 buckwheat, 4 mustard, oats, chickory	Ripe	4-220	No	No	No	.....	*
Wollny, Ewald[17]	1877	13x20-22x20	*	1	1 corn, 1 oats, 1 peas, etc	Ripe	5-48	No	Yes	P'rtly	.....	Outdoors
Willard, R. E., and Humbert, E. P.	1913	27x48	*	2	Wheat, alfalfa, soy beans	Ripe	*	No	Not wheat	No	*	Field

***Information lacking. In practically all of these cases no statement was made in the article reviewed.**
See p. 38 for footnotes.

FACTORS INFLUENCING TRANSPIRATION IN FACT.[1]

The phenomenon of transpiration or evaporation from plants is subject to many influences. Some of these are very profound in their effect, while others are comparatively insignificant. In the following outline is given a rather inclusive list of these factors. They are either environmental in nature or inherent plant characters. Space will not be taken in this bulletin to discuss each of these. However, the experimental data with discussions which follow concern most of these influences that are important.

These footnotes refer to the table on the preceding page.

[1] This list of investigators is complete so far as the writer has been able to determine, and there are probably not many omissions.

[2] Briggs and Shantz tested over 100 different crops and varieties, these in the table being merely representative, and planted respectively at the rates indicated. The crops were harvested immature in several tests.

[3] Daszewski gives a table in which Wilm's (1899) data with potatoes are reduced to dry weight. He also gives the composition of the crop.

[4] Dehérain. The difference between seepage water and rainfall was regarded as the amount used by the crop.

[5] Heinrich grew his plants in nutrient solution without soil or sand.

[6] King partly excluded the rain in 1894. He also tested barley, oats, and peas.

[7] Khankhoje harvested some plants at an earlier stage to compare with mature plants.

[8] Leather tested wheat, barley, oats, linseed, sarson, peas, gram, maize, uar, rice, murwa, kodo, rahar, and guar.

[9] Liebscher mentions damage from an overabundance of rain, so his pots probably stood in the open.

[10] Marié-Davy. In 1876, part of the pots were exposed to rain and part were not. Apparently correction was made for the rainfall. In 1874 and 1875 only the yield of grain is given, while in 1876 the weights of stems were 692-1,065 grams, and the grain weights were 262-474 grams. Only the large potometers were used in 1875 and 1876.

[11] Pfeiffer, et al., used an unsatisfactory method for correcting evaporation.

[12] Schroeder. Evaporation was not very satisfactorily prevented in 1893.

[13] Seelhorst apparently grew his plants outdoors and moved them into a shelter at time of rain, altho this is not definitely stated.

[14] Sorauer tested a number of additional species, but the methods are so faulty as not to be applicable. Most of Sorauer's tests must be included with the seedling stage.

[15] Widtsoe. His illustrations indicate that the soil was much overcropped with corn.

[16] Wilms based the transpiration on green weight of tubers, but this was reduced to dry weight by Daszewski in 1900.

[17] Wollny tested nine varieties in all, including corn, barley, oats, millet, buckwheat, peas, rape, mustard, and sunflowers. The evaporation was almost prevented by means of a cover, but bare pots were used for correction. Wollny states that the rain was excluded by means of covers which had only a small hole in the center for the plant. Without sealing the opening about the plant, it is possible by this method that rain is conducted down the outside of the plant into the pot.

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[1] Contrasted with "Factors influencing transpiration determinations with rooted plants in pots as sources of experimental error,"—p. 27.

OUTLINE OF FACTORS INFLUENCING TRANSPIRATION IN FACT.

A. Atmospheric (or climatic).
   1. Temperature.
   2. Relative humidity.
   3. Wind velocity.
   4. Light.
   5. Radiant heat. (Radiation.)
   6. Composition of air.
   7. Air pressure.
   8. Evaporation rate of free water as a summary expression of the climatic factors.

B. Soil.
   1. Composition.
   2. Available fertility (strength of soil solution).
   3. Available moisture content.
   4. Soil texture.
   5. Soil temperature.

C. Plant characters.
   1. Root development.
   2. Leaf-area.
   3. Arrangement of leaves.
   4. Structure (especially of leaves).
   5. Dry weight of plant (not a determining but a resultant factor).
   6. Density of cell sap (osmotic pressure).
   7. Relative ability to withstand periods of drouth.
   8. Heat generated within plant as result of chemical activity.
   9. Age of plant.
   10. Moisture content of leaf.
   11. Cooling effect exerted upon plant itself by transpiration.
   12. Vital element in the plant.
       (An indirect factor as it affects physical conditions within the leaf.)
   13. Disease.

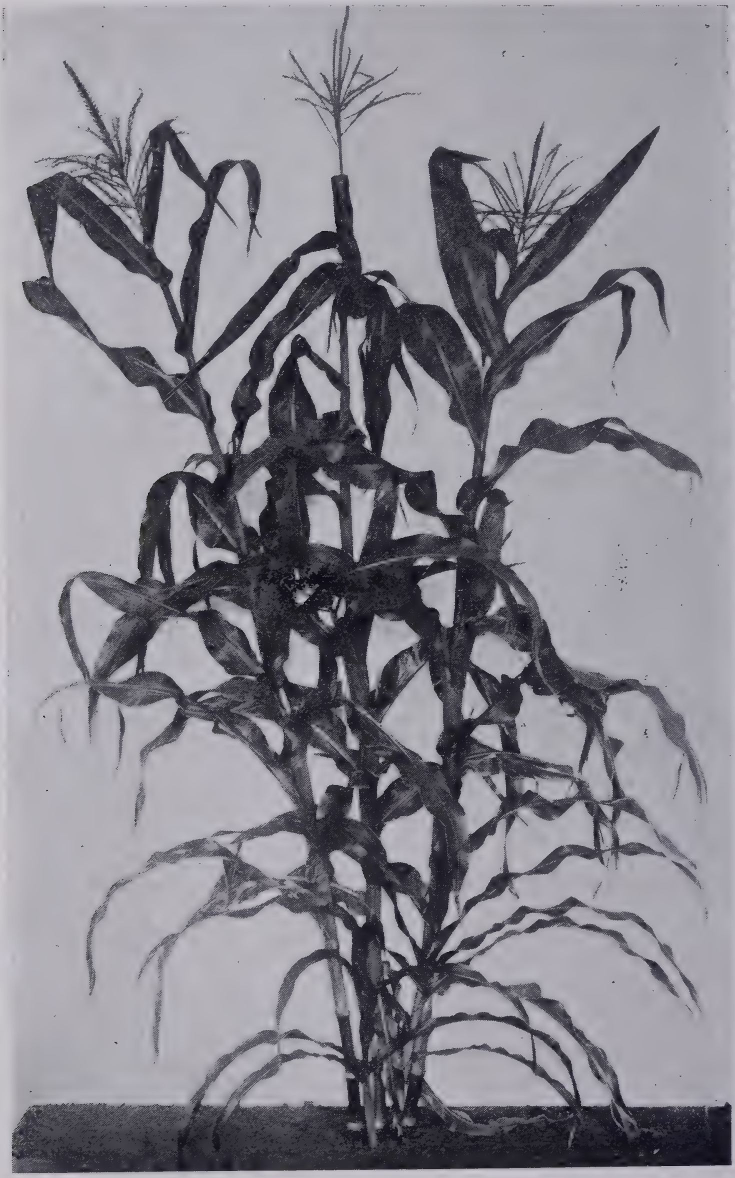

Fig. 1.—A typical hill of corn adapted to eastern Nebraska. A hill with three such plants has approximately 3,600 square inches of leaf-area (counting only one side of the leaf, or 7,200 square inches including both sides), from which water evaporates. An acre contains 3,556 hills planted 3 feet 6 inches apart. Such an acre has 4 acres of leaf-surface.

PART II. THE EXPERIMENTS.

The investigations which follow have been conducted at the Agricultural Experiment Station of Nebraska, Lincoln, Nebr. Most of the data have been secured during the last three years (1912-1914) and have not been published before. In some instances earlier work at this Station has been continued along similar lines or extended, in which case the related data have been reproduced here, and reference given to the earlier publications.

PROBLEMS UNDER INVESTIGATION.

The general project has been to study the relation of environmental factors and plant characters to the water requirements of crops. Under environment, climatic factors, soil fertility, and soil moisture have been investigated. Evaporation from a free water surface, as a summary expression of the various climatic factors, has been studied at different elevations in corn and small-grain fields. Concerning plant characters a number of measurements have been made of all plants tested, in order to observe any possible correlation. During one year (1914) the relative water requirements were determined of corn secured from humid and semiarid districts, of corn varieties differing in growth habits, and of a number of sorghum varieties and sunflowers in comparison with corn. Histological studies were made to determine whether there may be any structural correlations. Ash determinations were made for studying the relation between transpiration and the intake of soil solutes.

Thus, it is seen that all the investigations, with the exception of 1914, have been made with corn. It is believed that in this way general principles concerning transpiration may be established which will apply not only to corn, but to many other crops as well.

In connection with the general project, possible sources of experimental error have been investigated.

METHODS OF COMPILING DATA.

The data contained in the following general tables consist of two distinct kinds, namely, (1) exact quantitative measurements and (2) ratios between these exact measurements. To illustrate by referring to Table 4, columns 2, 3, 4, 5, 6, 7, and 13 are exact measurements, while columns 8, 9, 10, 11, and 12 are ratios. It is important to understand the manner of compiling the average data for the duplicate potometers. Those columns in the tables which contain exact quantitative measurements are averaged by adding the column and dividing by the number of duplicates.

In the case of the ratio columns, the average results are obtained by finding the ratio of the averages for the other columns, rather than by averaging the ratio columns.

In case of the ratios in the average summaries we have, then, the ratio of averages rather than an average of ratios.

In most cases the differences obtained by the two methods of calculating are rather slight and immaterial. Both methods appear to be mathematically correct, but the one employed in this bulletin appears to be more desirable. From the performance standpoint, it is important to know what are the production and the amount of water transpired in the aggregate, and then to establish a ratio between these average results. Table 4, column 8, illustrates an instance where the method of calculating is rather vital. In a test to determine the effect of the size of the potometer as a source of experimental error, the smallest size limited the plant growth to such an extent that ear production was almost impossible, and only one plant out of four succeeded in producing a small ear. Consequently, for practical purposes, the amount of water transpired by the four plants must be charged up against the one small ear. This can only be done by determining the ratio of averages.

In all cases where the data of two or more years have been averaged together in a summary table, the average of ratios was determined rather than the ratio of averages, as was done in the case of averaging different individuals within a single year. This was done in order to avoid overemphasizing in the average ratio the seasonal effects of a given year. For these reasons the summaries in this bulletin may not appear to be quite mathematically correct, but they are in fact merely subject to the well-known effects of averages.

The probable error has not been computed for any of the data in this bulletin, altho the potometers have been replicated from four to eight times. A calculation of the probable error where the frequency is so small would appear to be of little value to establish the reliability of the results. Where small numbers are averaged, it is entirely probable that the actual error in certain groups of duplicates will be consistently and abnormally high above the correct mean, while in others it will be below the correct mean. The actual error may be large in these cases due to averaging either high or low extremes, while the computed probable error may be very small, due to consistency of the individuals averaged. Again, both high and low extremes may fall within a group to be averaged, so that the average result will be correct, altho the computed probable error is high. Illustrations of such grouping may be seen in Table 12.

All measurement determinations made in these experiments are expressed in the "regular" system, namely inches. Thus, leaf-areas and free water surfaces are indicated in square inches. This probably has an advantage in being more readily interpreted.

All weights of crop and of water used are expressed in the "metric" system, because the smaller units of weight possess an advantage in these calculations.

The scientific ideal no doubt would be to express all weights and measures uniformly in either the "metric" or "regular" system.

METHODS OF DETERMINING THE YIELD AND LEAF-AREA.

The crop was in all cases reduced to a moisture-free basis by drying to a constant weight in an electric oven at 110° C. The oven used was a specially constructed Freas oven, having a drying chamber 36 by 24 by 48 inches. The plants were pulled from the ground and the roots cut away from the base of the stalk. The dry matter harvested included the entire plant except the roots. It would be of interest to know the weight of the roots as well, but it seemed impossible to make a reliable separation of the roots of the crop from roots and other organic matter previously in the soil. The leaves were gathered from the plants as they ripened.

The leaf-area of the corn plants was determined when full grown, as in earlier experiments, by taking three-fourths of the product of the length by the maximum width of the individual leaves and adding together these products for the total leaf-area. This method is discussed by Montgomery (1911, p. 113).

A distinction should be observed between "leaf-area" and "leaf-surface" as used in this bulletin. The latter is twice the area of the former, in that each leaf has two surfaces.

METHODS OF INVESTIGATION.

LOCATION OF EXPERIMENTS AND MATURITY OF PLANTS.

All transpiration measurements were made with rooted plants grown from the outset in potometers filled with soil. They may be grouped according to their location, as experiments conducted either in the cornfield or in the greenhouse. The greenhouse was used for only a comparatively small portion of the determinations, namely, the measurement of the effect of differences in relative atmospheric humidity upon transpiration. All plants were grown to maturity except those in the greenhouse, which were harvested at the silking stage.

DESCRIPTION OF POTOMET RS USED.

Three types of potometers were used, according to the nature of the experiment. Each proved admirably suited for its special requirements. These have been described in previous publications, but for convenience and a few slight modifications will be assembled and restated here.

In the field experiments the potometers stood in walled-up pits of such depth that their tops were on a level with the adjoining field. This field was planted to corn and furnished rather normal cornfield surroundings.

POTOMETER WITH COIL-WATERING DEVICE.[1]

The type of potometer illustrated below (Fig. 2) was designed for experiments where uniform partial soil saturation or frequent weighings were desired. To be exact, it was used in all soil saturation experiments during 1910, 1913, and 1914, and in the 1911 soil fertility experiment. All hourly and daily correlations in the field with climatic factors were made with the corn plants growing in this type.

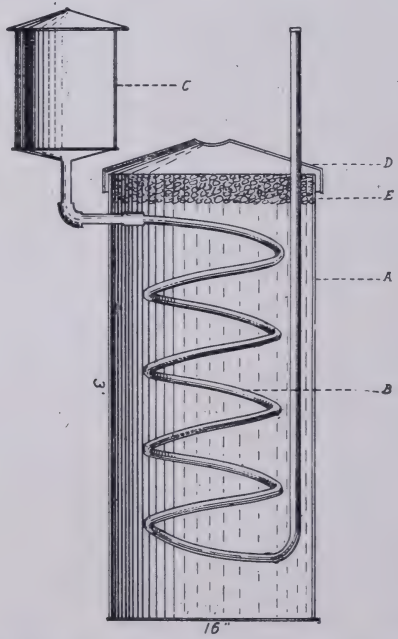

Fig. 2.—Potometer with coil-watering device. A, galvanized-iron pot filled with soil; B, perforated coil for distributing water; C, 6-quart can to which water is added; D, galvanized-iron lid; E, 3-inch gravel mulch.

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[1] This type of potometer was first used and described by Kiesselbach and Montgomery (1911).

The potometers were 16 inches in diameter and 3 feet deep. The amount of soil contents varied somewhat from year to year but was approximately 250 pounds of moisture-free soil. The exact amount is stated with each experiment. A 3-inch layer of gravel served to reduce surface soil moisture evaporation. Rain was excluded by means of a loosely fitting galvanized-iron lid having a 4-inch opening for the plant. After the plant had attained a height of 18 inches a further protection against the entrance of rain was added in the form of an oilcloth covering over the opening about the plant, which was sealed to the stalk by means of a 3-inch collar of plastic modeling clay (plastocene) illustrated in Figure 3.

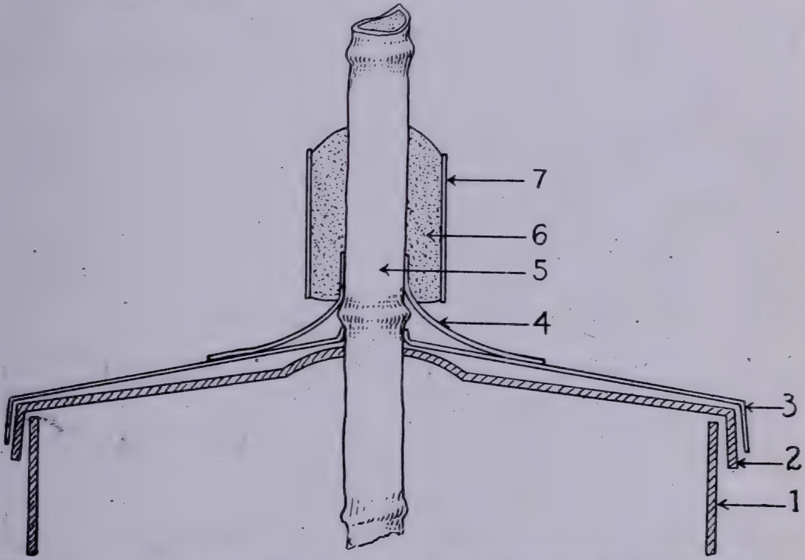

Fig. 3.—Potometer lid showing oilcloth and plastocene seal about the plant. The leaves of a corn plant act as a funnel, and it has been determined that without this close seal at the base approximately 6½ pounds of water will be conducted along the stalk of a full-grown plant into the potometer for each inch of rain. The seal is so made that the plant may sway in the wind without disturbing the seal.
1, potometer wall; 2, galvanized-iron lid; 3, oilcloth; 4, oilcloth; 5, corn stalk; 6, plastocene; 7, oilcloth girdle.

Buried in the soil and connected at the top with a covered 6-quart can, was a spiral coil made of ⅜-inch brass tubing 16 feet in length and perforated every 8 inches. All water was added in weighed quantities thru the small can and distributed rather uniformly thruout the soil by means of the perforated coil.

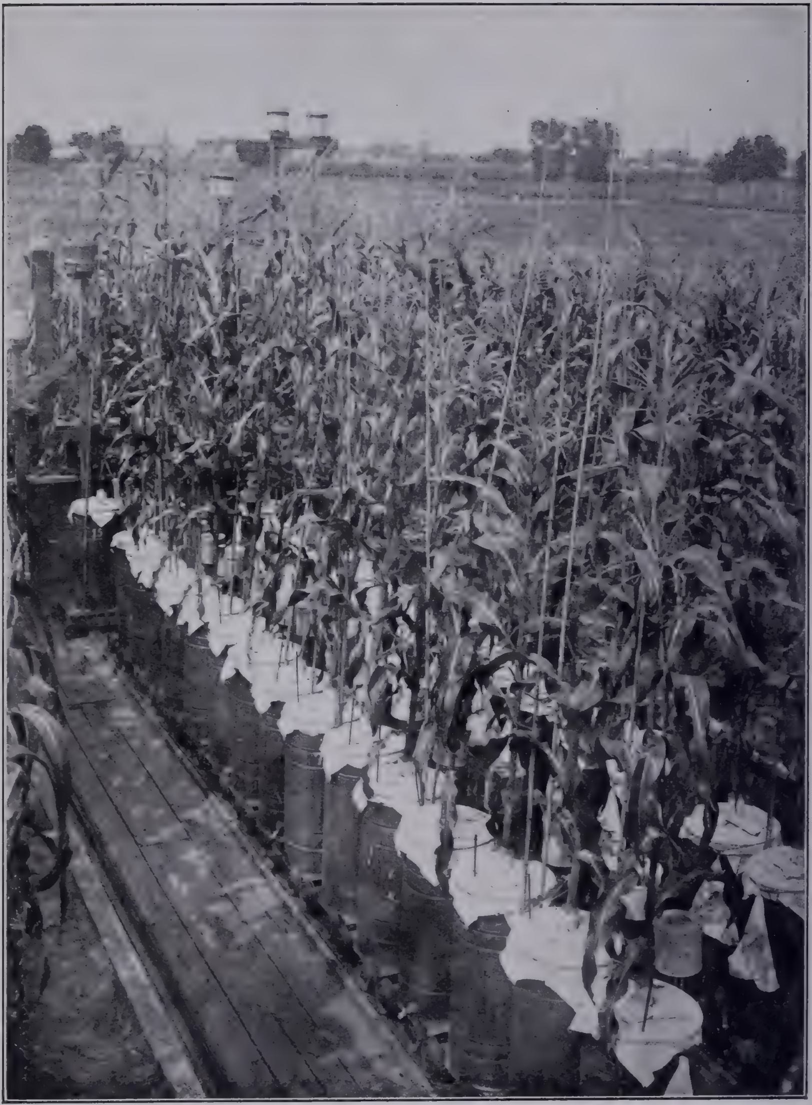

Fig. 4.—General view of soil saturation series pit, 1914, showing potometers on trucks, and part of the free-water-surface evaporation jars at different elevations in the background. The bamboo pole on each potometer supports the plant in case of strong wind.

This watering device necessitates frequent weighing in order to determine the necessary quantity of water to replace that lost by transpiration and thus maintain a fairly constant degree of saturation.

All water was weighed accurately in grams before being added.

On the floor of the pit were three double tracks upon which the potometers, standing on small iron trucks, could be rolled back and forth. (Fig. 4.) At any one time the potometers stood on the middle and one of the outside tracks. At one end of the three tracks, a fourth track at a right angle to the others was

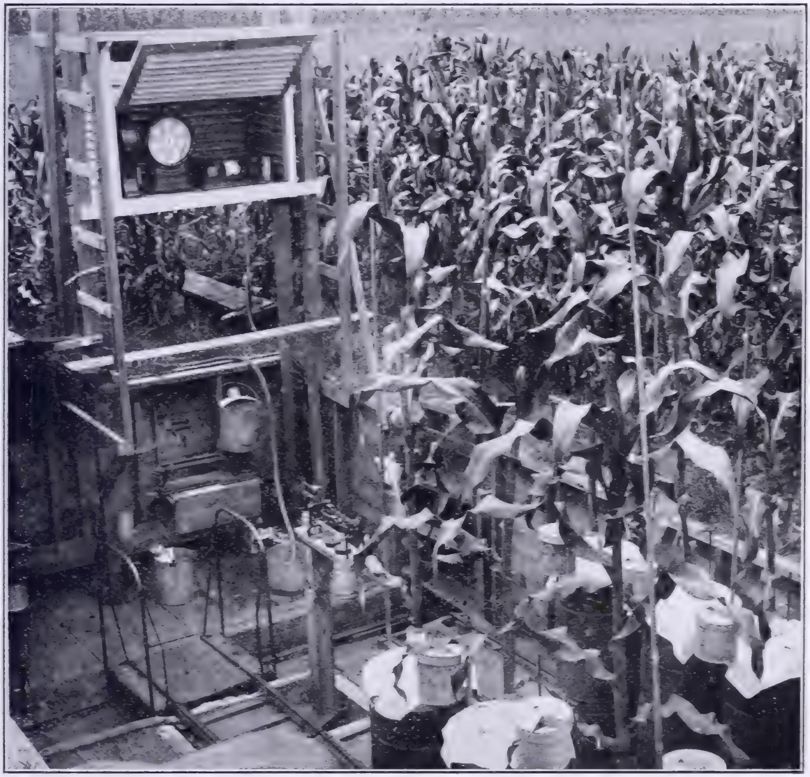

Fig. 5.—Detailed view showing arrangement for weighing potometers to determine the daily use of water by corn plants. The shelter contains self-recording instruments for temperature, relative humidity, and wind velocity in the cornfield, where these transpiration experiments are conducted. Above the shelter were a wind gauge and rain gauge.

sunk in a depression so that a truck running back and forth connected on a level with the three main tracks. A platform scale graduated to one-hundredth of a pound was located permanently at the end of the middle track. (Fig. 5.) When about to be weighed, the potometers on the middle track would first be rolled individually upon the scale, weighed, rolled upon the switching truck, and moved back upon the empty receiving track. The potometers in the second row were then switched back upon the middle track and weighed while passing over the scale. This arrangement for weighing and switching the potometers is much better than that described in the Twenty-fourth Annual Report of this Station. It is a great advantage to have the scale permanently located.

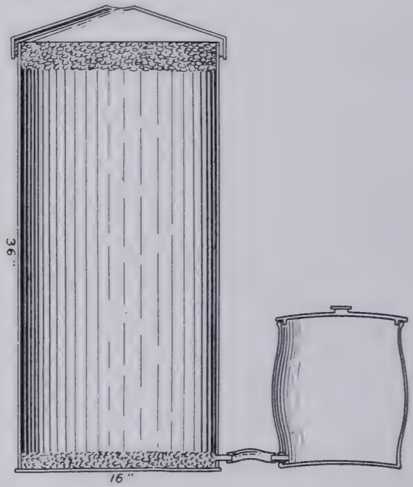

Fig. 6.—Potometer with subirrigation-watering device for maintaining a constant moisture supply.

POTOMETER WITH SUBIRRIGATION-WATERING DEVICE.[1]

In experiments where soil moisture is not a variable factor under investigation and the object is to determine the total amount of water transpired during the growth of the plant, the watering device shown in Figure 6 is very simple in operation and is very satisfactory.

Except in experiments to determine the effect of the amount of soil, the potometers were of the same size as those just described, 16 by 36 inches, and were made in the same manner. Weighed quantities of water are added to covered 4-gallon, glazed earthen jars, which stand on a level with and are connected at the bottom to the potometers. A constant supply of water is kept in the jars so that the soil-moisture content is continually kept fairly uniform in all potometers. The water runs from the jar thru a rubber connecting tube into a 1-inch, gravel water bed in the bottom of the potometer and rises into the soil by capillarity. The distribution of moisture thruout the soil mass is shown in Table 2. Evaporation is prevented and rainfall excluded by the same devices as with the previous potometer.

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[1] This type of potometer was first used and described by Montgomery (1911).

The total water used is found by taking the total weight of water applied minus the amount remaining in the jar at the close of the experiment, and either adding or subtracting the difference in initial and final weight of the potometer, according to whether it has lost or gained in weight.

Figure 7 illustrates the manner of weighing these potometers.

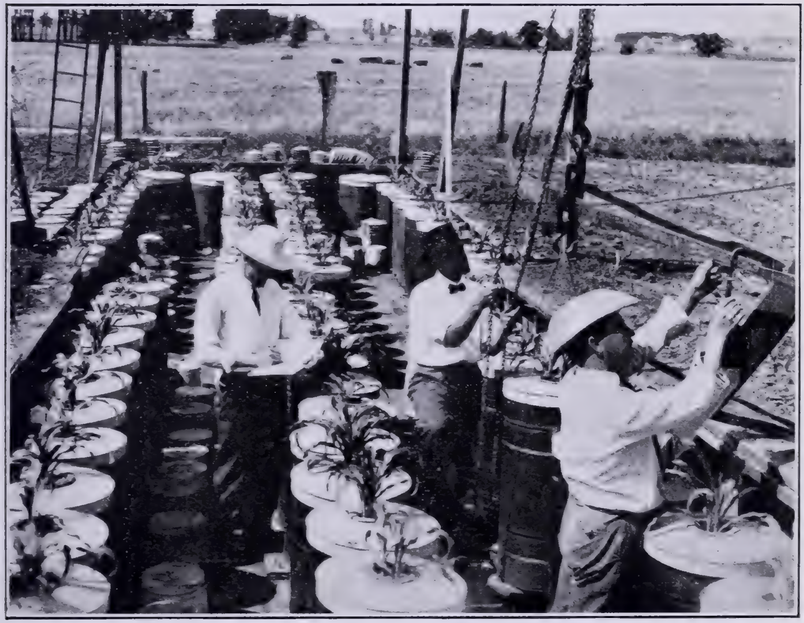

Fig. 7.—Method of weighing potometers where only initial and final weights are made to determine the total water used. The potometer is lifted by means of differential block and tackle and weighed on steelyard of 2,000 pounds capacity. At this stage, the corn was reduced to one plant per potometer, several kernels having been planted to insure a full stand.

They are lifted by means of a differential block and tackle suspending a steelyard graduated in half pounds.

LABORATORY POTOMETER.[1]

Figure 8 illustrates the type of potometer used in part of the greenhouse experiments. Corn plants grown in potometers of this size must be harvested at an early stage before the small quantity of soil has become a limiting factor in growth.

The apparatus consists of a 4-gallon, glazed earthen jar, filled with approximately 35 pounds of fertile soil. An inverted, porous, clay flower pot is placed in the bottom of the jar and connected with the surface by two $\frac{3}{8}$-inch glass tubes. Water is added in weighed quantities thru one of the tubes by means of a funnel having a rubber-tube connection. The second tube provides for the escape of the replaced air, as water is added. The flower pot serves both as a water chamber and as an aerating device. By frequent weighing and replacement of water, any amount of soil moisture may be rather constantly maintained. Surface evaporation is prevented either by sealing with plastic modeling clay (plastocene) or by covering with paraffined paper weighted down with gravel. The water and potometers are weighed in grams on a Troemner balance.

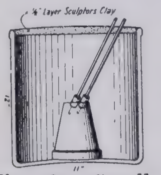

Fig. 8.—Small laboratory potometer.

RELATIVE GROWTH IN FIELD POTOMETERS AND IN FIELD.

By growing one corn plant in the standard potometers, 16 by 36 inches, and supplying fertile soil, the vegetative growth and ear development is fully equal to that of plants in a normal cornfield under favorable conditions. Figure 9 shows a mature crop of plants ready to be harvested.

Table 1 shows the comparative development of Hogue's Yellow Dent corn grown in the potometers and in the field during four years. During the first three years given, the corn was grown two plants per hill, while in 1914, three plants per hill were grown. The hills were 3.5 feet apart.

DISTRIBUTION OF MOISTURE IN SOIL.

Table 2 shows the moisture content in foot sections in representative potometers of the two large field types. The data for the potometers with the coil show how a relatively low degree of saturation may be maintained uniformly thruout the soil.

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[1] This type of potometer was first used and described by Kiesselbach (1910).

TABLE 1.—*Relative development of corn plants in the potometers and in the field. (Hogue's Yellow Dent corn.)*[1]

Character	1907		1909		1910		1914		Average	
	Field	Potometers	Field	Potometers	Field	Potometers	Field	Potometers	Field	Potometers
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Dry weight stalk... (grams)	136	173	149	171	170	215	91	162	136	180
Dry weight ear[2].... (grams)	246	283	218	252	264	261	133	242	215	259
Dry weight leaves.. (grams)	51	48	45	38	49	43	43	39	47	42
Total dry wt. plant.. (grams)	433	504	412	461	483	519	267	443	399	482
Leaf-area per plant. (sq. in.)	1,030	1,258	1,261	1,179	1,221	1,166	1,013	1,193	1,131	1,199
Leaf-area pr.gr.dry wt. (sq.in)	2.4	2.5	3.1	2.6	2.5	2.3	3.8	2.70	2.9	2.5
Ratio ear wt. to stalk wt...	1.8	1.6	1.5	1.5	1.6	1.2	1.5	1.50	1.6	1.4
Yield per acre..... (bushels)	55.1	......	40.6	......	53.1	....	49	....	....	....
No. plants grown per hill...	2	......	2	......	2	....	3	....	....	....

[1] The data for 1907, 1909, and 1910 are compiled from Montgomery (1910, pp. 153 and 156) by averaging together all Hogue's Yellow Dent strains of corn for each year.

[2] The apparent discrepancy between the average ear production per plant and the yield per acre is due to the selection of only 20 plants each year for the detail data, which did not prove to be quite representative of the entire plat.

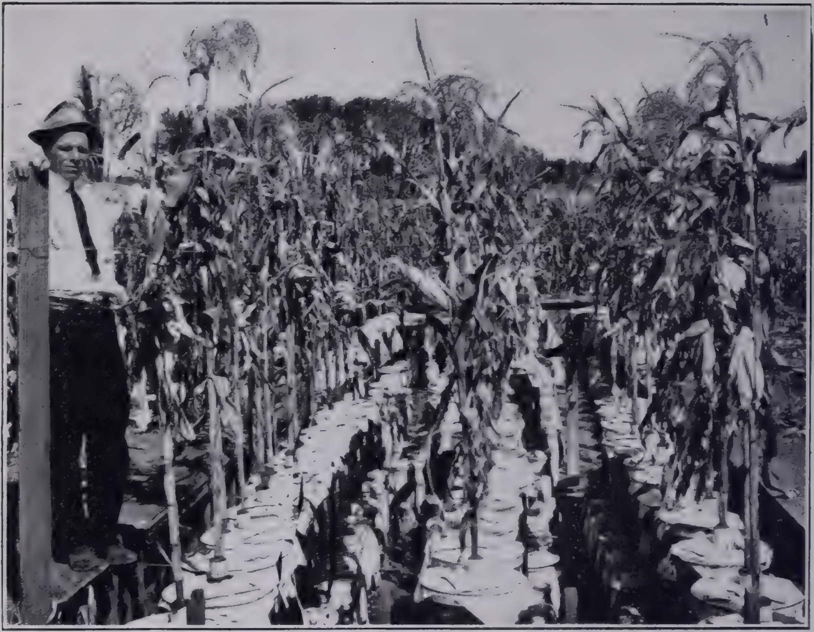

Fig. 9.—A mature crop of corn grown in the potometers. Note the plastocene collars at the base of the plants for excluding rain. Also note the normal development of the plants.

In those potometers to which a constant supply of water was added thru the jar at the bottom, the soil naturally contained all of the water it could take up by capillarity. The lower foot of soil contained 4 per cent more moisture based on dry soil weight than did the upper foot, while the middle section was intermediate. Variation in the total moisture content of the duplicate potometers was less than 3 per cent. So small a difference will not materially affect the transpiration rate when water is plentiful.

WATER LOSS BY EVAPORATION FROM THE POTOMETERS.

Since neither the potometers nor the water jars were sealed air-tight, it was to be expected that a small amount of water would be lost by evaporation in addition to that used by the plant. To determine the approximate amount of such loss, three uncropped potometers were tested during two years, 1913 and 1914. The water jars were full of water thruout the season and consequently a maximum amount evaporated from them.

The results contained in Table 3 show an extreme individual variation of 2.35 kilograms and an average total loss of 3.4 kilograms for 1913. In 1914 the extreme variation was 1.66 kilograms, and the average total loss was 3.02 kilograms. No attempt has been made to correct the experimental data for such evaporation. For comparative purposes, one would conclude that an error exists of about 2 kilograms per plant in relative total transpiration when grown to maturity, while on an average the total transpiration for all plants is about 3 kilograms too high. The percentage of error is small and has been disregarded.

During two months in the greenhouse in 1912, four of the small 4-gallon laboratory potometers described on page 50 lost an average of 420 grams of water, when left uncropped.

TABLE 2.—*Distribution of moisture in potometers with the two methods of water addition used in the Nebraska experiments. 1914.*

Potometer No.	Water in first foot. Dry soil basis	Water in second foot. Dry soil basis	Water in third foot. Dry soil basis	Average
(1)	*Per cent* (2)	*Per cent* (3)	*Per cent* (4)	*Per cent* (5)
	WATER ADDED THRU PERFORATED SPIRAL COIL			
1	17.4	17.5	16.4	17.1
2	17.9	17.7	18.2	17.9
3	17.1	16.2	17.2	17.0
4	17.5	17.1	16.3	17.0
Average	17.5	17.1	17.0	17.2
	WATER ADDED THRU JAR AT BASE OF POTOMETER			
1	31.7	33.4	34.3	33.1
2	29.7	30.6	33.4	31.2
3	31.2	34.0	35.2	33.5
4	29.4	33.2	35.5	32.7
Average	30.5	32.8	34.6	32.6

TABLE 3.—*Amount of water lost from check potometers in which no plants were grown but otherwise treated the same as the cropped potometers.*

Year	Amount of water lost			Average
	Potometer No. 1	Potometer No. 2	Potometer No. 3	
	Kilograms	*Kilograms*	*Kilograms*	*Kilograms*
1913	2.09	4.44	3.69	3.40
1914	2.70	2.35	4.01	3.02

EFFECT OF SIZE OF POTOMETER AS A SOURCE OF EXPERIMENTAL ERROR.[1]

Not only transpiration but extensive fertilizer and other cultural experiments as well have been conducted in pots by various investigators. They are used largely in greenhouse experiments, but some agricultural experiment stations have pot cultures located in the field where they may be exposed to the natural elements. For convenience in handling and economy of space, the pots are usually rather small. This is especially true of those used in greenhouses. In order to secure accurate data to help interpret the results of other investigators and to determine the reliability of our own work, the relative growth

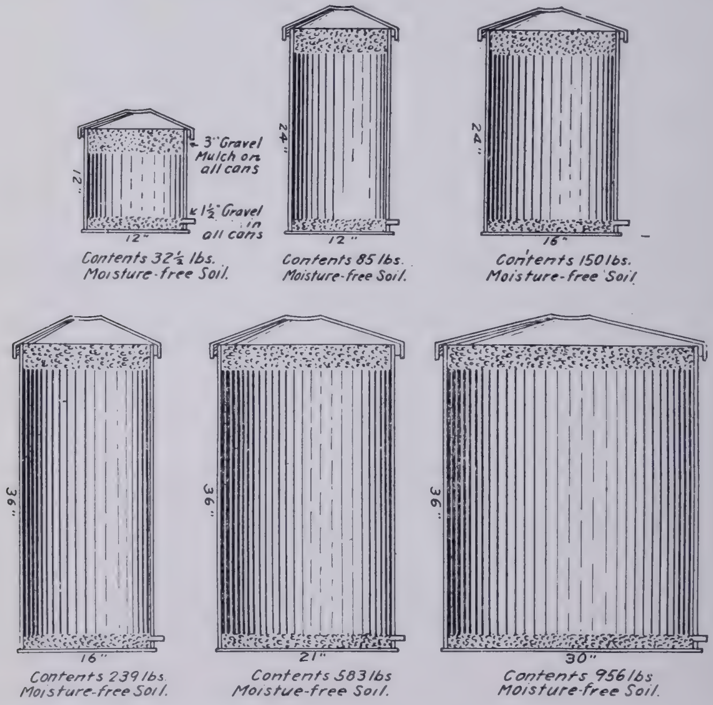

Fig. 10.—The different sizes of potometers used to determine the effect of the quantity of soil upon growth and transpiration.

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[1] References concerning the effect of soil limitation: Hellriegel (1883), Leather (1910, 1911), and Seelhorst and Bünger (1907).

and water requirements of corn were studied in potometers of six sizes containing respectively 32.5, 85, 150, 239, 583, and 956 pounds of moisture-free soil. The soil was a fertile loam from the surface six inches of a productive cultivated field, and was uniform thruout all the potometers. The subirrigation type of potometer was used, and all growing conditions were uniform except the size of potometer and quantity of soil. The shorter potometers were elevated so that the top of all were on a level with the surrounding cornfield. A single stalk of Hogue's Yellow Dent corn was grown to maturity in the center of each potometer. All of the seed was secured from the middle of a single ear. A duplicate series was grown with all conditions identical with the first series, except that well-rotted sheep manure was mixed with the upper foot of soil in each potometer at the rate of 4 pounds per plant as it came from the pile, or 1.75 pounds of moisture-free manure. This rate per plant under average eastern Nebraska field conditions would amount to about 21 tons of moist manure, or 9 tons of moisture-free manure per acre, counting 10,668 plants per acre. Each size of potometer and method of treatment was replicated four times. Figure 10 illustrates the different sizes of potometers used.

Figure 11 shows the relative plant development in the potometers of different sizes, both without and with manure. A representative plant was chosen from each set. Figure 12 shows the actual ears harvested. Four plants were harvested in all but two sets. One plant in each set of the 16 by 36 inch and 30 by 36 inch potometers without manure was broken early by the wind, reducing the number to three plants. Several plants produced more than one ear.

The results of the experiments dealing with the size of potometers are given in Tables 4, 5, 6, and 7, and Charts 1 to 7.

A detailed study of the tables shows a very marked relationship between the amount of soil available to the plant and the growth and water requirements. An increase in the amount of soil rather consistently increased the ear weight, the total dry weight of the plant, and the total amount of water transpired. It decreased the amount of water used per unit of dry weight of plant, altho this decrease was not proportional to the increase in weight of plant nor to the increase in the amount of soil.

The addition of equal quantities of manure to the different sized potometers increased the average ear weight 722.5 per cent in the smallest and only 2.9 per cent in the largest potometers. The total dry weight per plant was increased 176.4 per cent in the smallest and only 7.2 per cent in the largest potometers. The total amount of water transpired per plant was increased

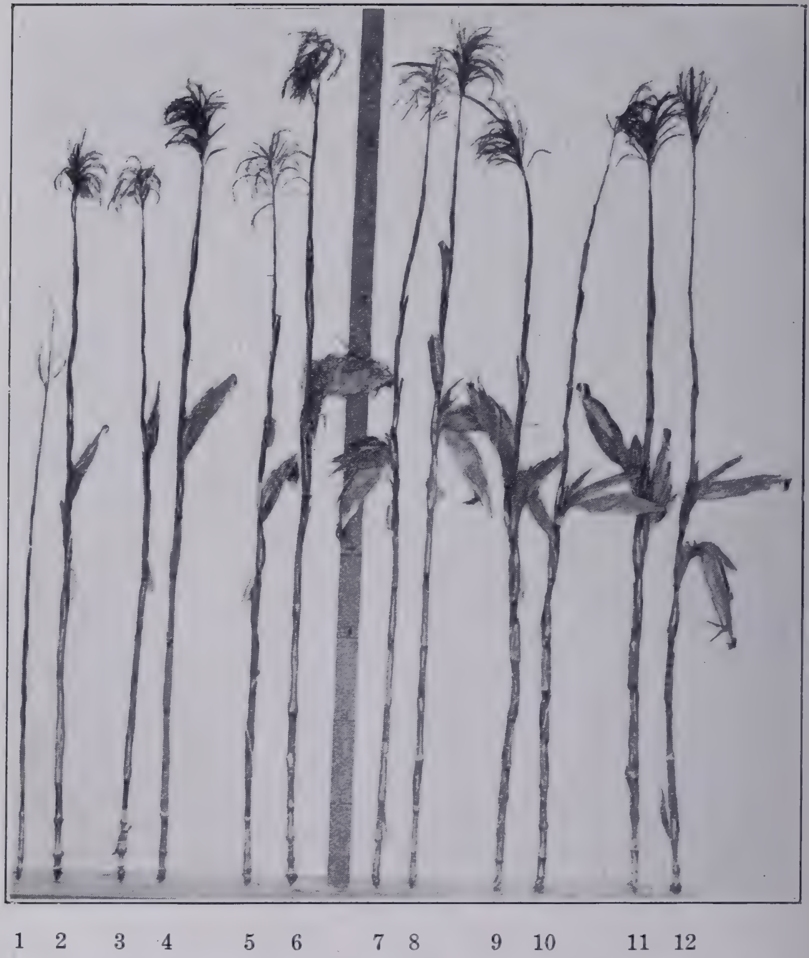

Fig. 11.—Representative plants grown in potometers of different sizes, without and with manure, to determine the effect of the size of the potometer as a source of experimental error in pot experiments. 1914. Reading from left to right: 1, potometer 12″x12″, without manure; 2, with manure; 3, potometer 12″x24″, without manure; 4, with manure; 5, potometer 16″x24″, without manure; 6, with manure; 7, potometer 16″x36″, without manure; 8, with manure; 9, potometer 21″x36″, without manure; 10, with manure; 11, potometer 30″x36″, without manure; 12, with manure. See Tables 4 to 7.

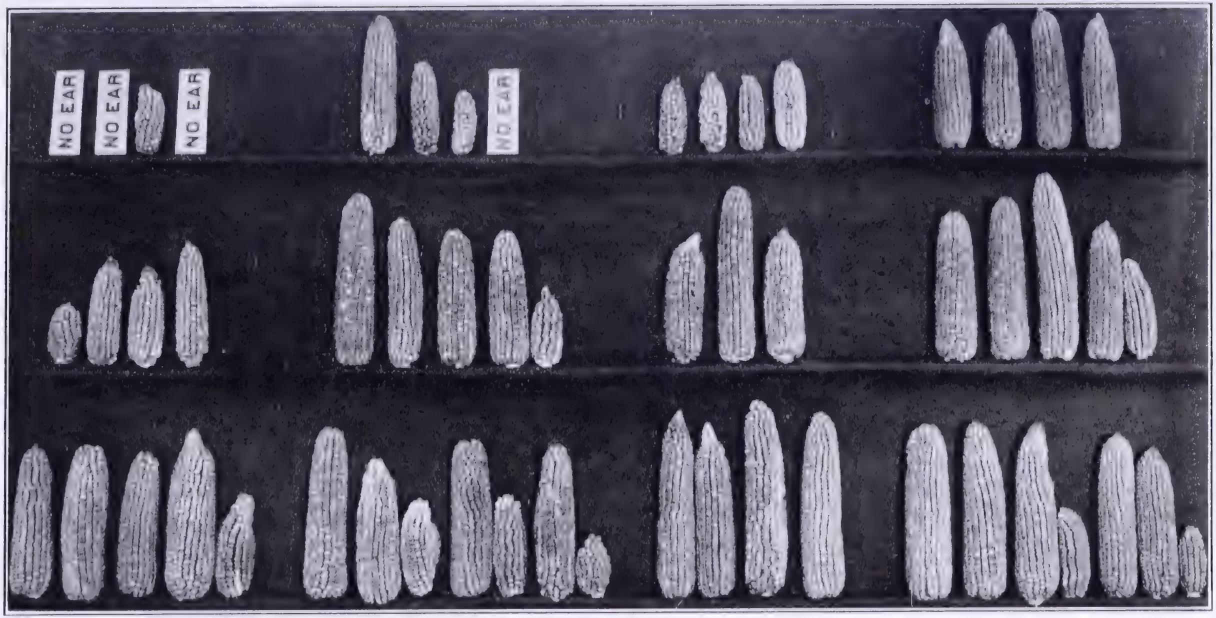

Fig. 12. Ears produced in potometers of different sizes, without and with manure. 1914. Groups No. 7 and 11 contain only three potometers, one plant in each having been broken early in the season. Reading from left to right: 1, potometer 12″x12″, without manure; 2, with manure; 3, potometer 12″x24″, without manure; 4, with manure; 5, potometer 16″x24″, without manure; 6, with manure; 7, potometer 16″x36″, without manure; 8, with manure; 9, potometer 21″x36″, without manure; 10, with manure; 11, potometer 30″x36″, without manure; 12, with manure. See Tables 4 to 7.

TABLE 4.—*Effect of size of potometer upon growth and water requirements of corn. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area[1]	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	Grams (2)	Grams (3)	Grams (4)	Grams (5)	Kilograms (6)	Sq. in. (7)	Grams (8)	Grams (9)	Grams (10)	Sq. in. (11)	(12)	Inches (13)
SIZE OF POTOMETER 12″x12″, CONTAINING 32.5 LBS. MOISTURE-FREE SOIL WITHOUT MANURE												
53	68	0	27	95	41.420	786	....	436.00	52.69	8.27	....	82
54	67	0	25	92	39.700	661	....	431.52	60.06	7.18	....	72
55	48	40	24	112	43.060	678	1,076.50	384.46	63.51	6.05	.83	82
56	64	0	27	91	36.180	694	....	397.56	52.13	7.63	....	68
Average....	61.75	10.00	25.75	97.50	40.090	704.75	4,009.00	411.20	56.89	7.23	.16	76
SIZE OF POTOMETER 12″x12″, CONTAINING 32.5 LBS. MOISTURE-FREE SOIL WITH 1.75 LBS. MOISTURE-FREE SHEEP MANURE												
49	145	213	39	397	120.700	1,190	566.66	304.03	101.43	3.04	1.47	106
50	98	84	34	216	60.090	1,135	715.33	278.19	52.94	5.25	.86	96
51	155	32	48	235	78.520	1,329	2,453.75	334.12	59.08	5.65	.21	106
52	190	0	40	230	87.610	1,014	....	380.91	86.40	4.41	....	98
Average....	147.00	82.25	40.25	269.50	86.730	1,167.00	1,054.47	321.80	74.32	4.33	.56	101
SIZE OF POTOMETER 12″x24″, CONTAINING 85 LBS. MOISTURE-FREE SOIL WITHOUT MANURE												
61	82	57	34	173	63.480	1,031	1,113.86	366.94	61.57	5.96	.70	104
62	114	59	41	214	87.250	1,255	1,478.81	407.71	69.52	5.86	.52	103
63	126	60	43	229	77.840	1,188	1,297.22	339.91	65.52	5.19	.48	102
64	93	77	37	207	70.010	1,184	909.22	338.21	59.13	5.72	.83	85
Average....	103.75	63.25	38.75	205.75	74.645	1,164.50	1,180.24	362.80	64.10	5.66	.61	99.7
SIZE OF POTOMETER 12″x24″, CONTAINING 85 LBS. MOISTURE-FREE SOIL WITH 1.75 LBS. MOISTURE-FREE SHEEP MANURE												
57	161	171	41	373	104.410	1,447	610.59	279.92	72.16	3.88	1.06	99
58	205	177	46	428	132.700	1,486	749.72	310.05	89.30	3.47	.86	111
59	139	210	47	396	142.660	1,366	679.33	360.25	104.44	3.45	1.51	108
60	183	185	43	411	120.350	1,113	650.50	292.82	108.13	2.71	1.01	106
Average....	172.00	185.75	44.25	402.00	125.030	1,353.00	673.11	311.10	92.41	3.37	1.08	106.0

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[1] The low water requirement per unit leaf-area in the small potometers has no significance. Being undernourished, the lower leaves dried up early and thus abnormally reduced the evaporating surface.

TABLE 4 CONTINUED.—*Effect of size of potometer upon growth and water requirements of corn.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
SIZE OF POTOMETER 16"x24", CONTAINING 150 LBS. MOISTURE-FREE SOIL WITHOUT MANURE												
69	200	48	56	304	104.510	1,534	2,177.29	343.78	68.13	5.05	.24	114
70	154	116	44	314	103.620	1,369	893.28	330.00	75.69	4.36	.75	108
71	154	120	36	310	101.910	1,188	849.25	328.74	85.78	3.83	.78	110
72	152	149	35	336	120.780	1,281	810.60	359.46	94.29	3.81	.98	108
Average....	165.00	108.25	42.75	316.00	107.705	1,343.0	994.96	341.00	80.24	4.25	.66	110.0
SIZE OF POTOMETER 16"x24", CONTAINING 150 LBS. MOISTURE-FREE SOIL WITH 1.75 LBS. MOISTURE-FREE SHEEP MANURE												
65	172	294	31	497	152.890	1,151	520.03	307.63	132.83	2.32	1.71	108
66	257	228	43	528	168.110	1,435	737.32	318.39	117.15	2.72	.89	114
67	256	254	49	559	165.880	1,401	653.07	296.74	118.40	2.51	.99	116
68	212	303	42	557	163.750	1,487	540.43	293.99	110.12	2.67	1.43	108
Average....	224.25	269.75	41.25	535.25	162.66	1,368.5	603.00	303.90	118.86	2.56	1.20	111.5
SIZE OF POTOMETER 16"x36", CONTAINING 239 LBS. MOISTURE-FREE SOIL WITHOUT MANURE												
23	100	197	33	330	94.980	1,071	482.13	287.82	88.68	3.24	1.97	102
36	166	291	42	499	135.160	1,364	464.47	270.86	99.09	2.73	1.75	123
81	219	237	42	498	137.890	1,145	581.87	276.89	120.43	2.30	1.08	124
Average....	161.70	241.70	39.00	442.30	122.677	1,193.3	507.57	277.35	102.81	2.70	1.49	116.3
SIZE OF POTOMETER 16"x36", CONTAINING 239 LBS. MOISTURE-FREE SOIL WITH 1.75 LBS. MOISTURE-FREE SHEEP MANURE												
7	313	276	58	647	181.590	1,478	657.93	280.66	122.85	2.28	.88	126
52	205	320	48	573	154.480	1,315	482.75	269.60	117.48	2.29	1.56	115
75	225	352	51	628	181.610	1,190	515.94	289.20	152.60	1.90	1.56	110
110	158	273	40	471	119.670	928	438.35	254.10	128.96	1.97	1.73	94
20	219	284	50	553	140.380	1,324	494.29	253.89	106.03	2.39	1.30	118
39	227	329	52	608	165.550	1,635	503.19	272.30	101.28	2.69	1.45	121
78	193	287	52	532	137.570	1,454	479.34	258.60	94.62	2.73	1.49	120
97	226	179	44	449	132.990	1,248	742.96	296.20	106.58	2.78	.79	110
Average....	220.75	287.50	49.40	557.60	151.730	1,321.5	527.76	272.10	114.82	2.37	1.30	114.3

TABLE 4 CONTINUED.—*Effect of size of potometer upon growth and water requirements of corn.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
SIZE OF POTOMETER 21″x36″, CONTAINING 583 LBS. MOISTURE-FREE SOIL WITHOUT MANURE												
27	272	246	52	570	164.350	1,198	668.09	288.33	137.19	2.10	.90	100
32	185	266	50	501	141.880	1,241	533.38	283.19	114.33	2.48	1.44	113
85	351	233	57	641	191.740	1,386	822.92	299.13	138.34	2.16	.66	120
90	290	451	58	799	231.290	1,408	512.84	289.47	164.27	1.76	1.56	114
Average	274.50	299.00	54.25	627.75	182.315	1,308.25	609.75	290.43	139.33	2.08	1.09	112
SIZE OF POTOMETER 21″x36″, CONTAINING 583 LBS. MOISTURE-FREE SOIL WITH 1.75 LBS. MOISTURE-FREE SHEEP MANURE												
26	325	345	49	719	184.250	1,388	534.06	256.26	132.75	1.93	1.06	130
33	309	339	54	702	191.830	1,372	565.87	273.26	139.82	1.95	1.10	106
84	322	373	63	758	199.320	1,499	534.37	262.96	132.98	1.98	1.16	112
91	294	308	50	652	186.500	1,361	605.52	286.04	137.03	2.09	1.05	110
Average	312.50	341.25	54.00	707.75	190.475	1,405.00	558.17	269.13	135.57	1.99	1.09	114
SIZE OF POTOMETER 30″x36″, CONTAINING 956 LBS. MOISTURE-FREE SOIL WITHOUT MANURE												
29	293	543	69	905	190.240	1,523	350.35	210.21	124.91	1.68	1.85	118
87	270	331	61	662	174.850	1,213	528.25	264.12	144.15	1.83	1.23	108
88	239	340	39	618	160.260	1,071	471.35	259.32	149.64	1.73	1.00	99
Average	267.33	404.67	56.33	728.30	175.117	1,269.00	432.74	240.45	138.00	1.74	1.51	108
SIZE OF POTOMETER 30″x36″, CONTAINING 956 LBS. MOISTURE-FREE SOIL WITH 1.75 LBS. MOISTURE-FREE SHEEP MANURE												
28	299	378	44	721	174.960	1,107	462.87	242.66	158.04	1.54	1.26	114
31	319	330	57	706	201.220	1,283	609.76	285.00	156.84	1.82	1.03	107
86	369	395	75	839	213.010	1,661	539.27	253.88	128.24	1.98	1.07	120
89	246	563	48	857	196.450	1,097	348.93	229.23	179.08	1.28	2.29	114
Average	308.25	416.50	56.00	780.75	196.410	1,287.00	471.57	251.57	152.61	1.65	1.35	114

TABLE 5.—*Effect in per cent of applying manure to potometers of different sizes. Results with manure are here expressed in per cent of results without manure. 1914.*

Size of potometer	Wt. moisture-free soil	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
		Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
Inches (1)	*Pounds* (2)	*Per cent* (3)	*Per cent* (4)	*Per cent* (5)	*Per cent* (6)	*Per cent* (7)	*Per cent* (8)	*Per cent* (9)	*Per cent* (10)	*Per cent* (11)	*Per cent* (12)	*Per cent* (13)	*Per cent* (14)
12x12	32.5	238.1	822.5	156.3	276.4	216.3	165.6	26.3	78.3	130.6	59.9	350.0	133.5
12x24	85	165.8	293.6	114.2	195.3	167.5	116.2	57.0	85.7	144.1	59.5	177.0	106.2
16x24	150	135.9	249.2	96.5	169.3	151.0	101.8	60.6	89.1	148.1	60.2	181.8	101.3
16x36	239	136.5	118.9	126.6	126.1	123.7	110.7	104.0	98.1	111.7	87.8	87.2	98.2
21x36	583	113.9	114.1	99.6	112.7	104.5	107.4	91.5	92.6	97.3	95.7	100.0	101.7
30x36	956	115.3	102.9	99.4	107.2	112.2	101.4	109.0	104.6	110.6	94.8	89.4	105.5

TABLE 6.—*Effect in per cent of increasing size of potometer. Results in the different sized potometers without manure are here expressed in per cent of the results in the smallest potometers without manure. 1914.*

Size of potometer	Wt. moisture-free soil	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
		Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
Inches (1)	*Pounds* (2)	*Per cent* (3)	*Per cent* (4)	*Per cent* (5)	*Per cent* (6)	*Per cent* (7)	*Per cent* (8)	*Per cent* (9)	*Per cent* (10)	*Per cent* (11)	*Per cent* (12)	*Per cent* (13)	*Per cent* (14)
12x12	32.5	100	100	100	100	100	100	100	100	100	100	100	100
12x24	85	168.0	632.5	150.5	211.0	186.2	165.2	29.4	88.2	112.7	78.3	381.3	131.3
16x24	150	267,2	1,082.3	166.0	324.1	268.7	190.6	24.8	82.9	141.0	58.8	412.5	144.7
16x36	239	261.9	2,417.0	151.4	453.6	306.0	169.3	12.7	67.4	180.7	37.3	931.3	153.0
21x36	583	444.5	2,990.0	210.7	643.8	454.8	185.6	15.2	70.6	244.9	28.8	681.3	147.4
30x36	956	432.9	4,046.7	218.8	747.0	436.8	180.0	10.8	58.5	242.6	24.1	943.8	142.1

TABLE 7.—*Summary showing effect of size of potometer upon growth and water requirements of corn. (Hogue's Yellow Dent corn.) 1914.*

Size of potometer	Moisture-free contents		No. of potometers averaged	Dry matter		Total water transpired	Transpiration per		Height of plant
	Soil	Manure		Ear	Total		gram dry wt. of ear	gram total dry matter	
Inches (1)	*Lbs.* (2)	*Lbs.* (3)	(4)	*Grams* (5)	*Grams* (6)	*Kilos.* (7)	*Grams* (8)	*Grams* (9)	*Inches* (10)
12x12	32.5	....	4	10	98	40.0	4,009	411	76
12x12	32.5	1.75	4	82	269	86.7	1,054	322	102
12x24	85.0	....	4	63	206	74.6	1,180	363	100
12x24	85.0	1.75	4	186	402	125.0	673	311	106
16x24	150	....	4	108	316	107.7	995	341	110
16x24	150	1.75	4	270	535	162.7	603	304	112
16x36	239	....	3	242	442	122.7	508	277	116
16x36	239	1.75	8	287	558	151.7	528	272	114
21x36	583	....	4	299	628	182.3	610	290	112
21x36	583	1.75	4	341	708	190.5	558	269	114
30x36	956	....	3	405	728	175.1	432	240	108
30x36	956	1.75	4	416	781	196.4	472	252	114

116.3 per cent in the smallest and 12.2 per cent in the largest. Manure reduced the water transpired per gram of dry weight 73.7 per cent for the ear and 21.7 per cent for the entire plant in the smallest potometers. For the largest potometers these data are somewhat inconsistent in that manure actually increased the water requirement for the ear and the entire plant 9.0 and 4.6 per cent, respectively. Doubtless, apparent inconsistencies are often due to the averaging together of an insufficient number of plants to overcome individuality. The reader is referred to the tables and charts for other relationships.

A preliminary test of three different sized potometers was made the preceding year, 1913. The results which follow in Table 8 substantiate in principle the more extensive 1914 data.

TABLE 8.—*Summary showing effect of size of potometer upon growth and water requirements of corn. 1913. (Hogue's Yellow Dent corn.)*

Size of potometer	Moisture-free soil	No. of potometers averaged	Dry matter				Total water transpired	Total leaf-area	Water requirement per			Leaf-area per gram dry wt.	Ratio of wt. of ear to wt. of stalk	Height of stalk
			Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram dry wt. of plant	sq. in. leaf-area			
Inches	*Pounds*		*Grams*	*Grams*	*Grams*	*Grams*	*Kilograms*	*Sq. in.*	*Grams*	*Grams*	*Grams*	*Sq. in.*		*Inches*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
12x24	86	4	104	28	33	165	90.01	680	3,215	546	132	4.1	.30	71
16x36	245	80	168	194	54	416	165.22	1,070	852	397	154	2.6	1.15	89
30x36	933	4	214	311	74	599	197.06	1,440	634	329	137	2.4	1.45	83

It is evident from the data that the limitation of the soil thru the size of the potometer may be a great source of error in pot experiments. It seriously affects not only the transpiration relationships but the entire development of the plant. A modified test of the effect of the size of the potometer is planned in which the amount of manure added will be varied according to the amount of soil contained by the potometers. The soil unit rather than the plant unit will be taken as the basis for comparison.

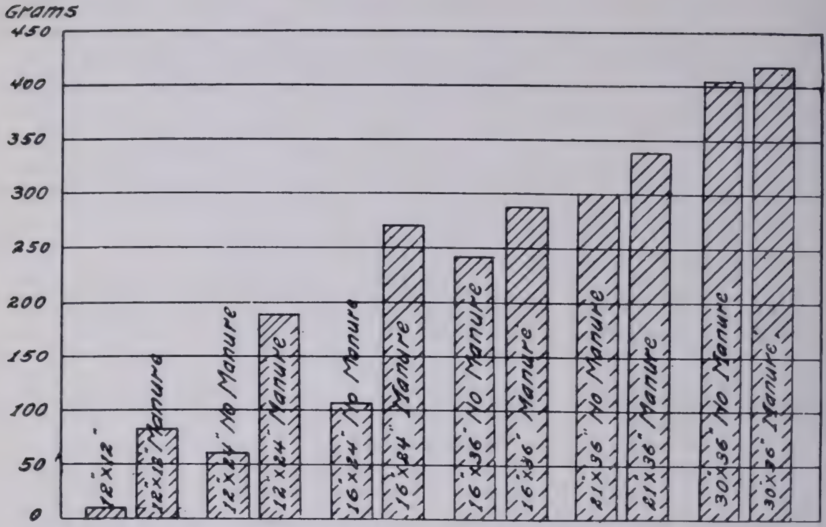

Chart I.—Effect of size of potometer on ear production with corn. 1914. See Table 7.

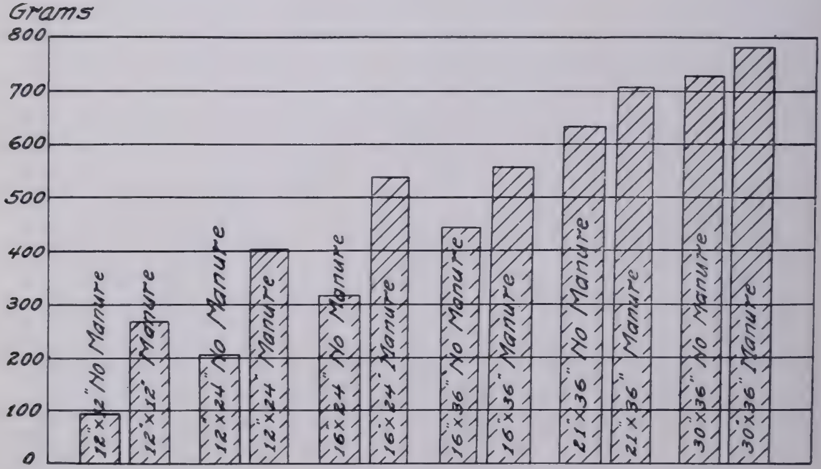

Chart II.—Effect of size of potometer on the total dry weight of the corn plant. 1914. See Table 7.

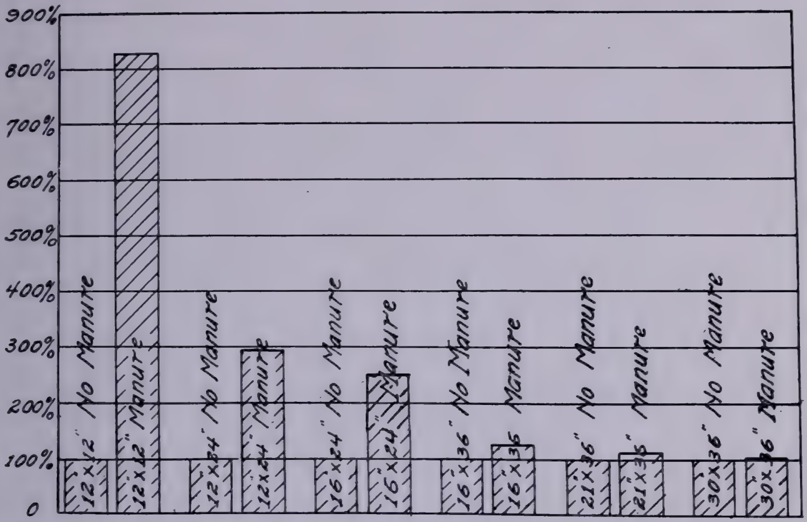

Chart III.—Effect on yield of ear from applying manure to potometers of different sizes. See Table 5.

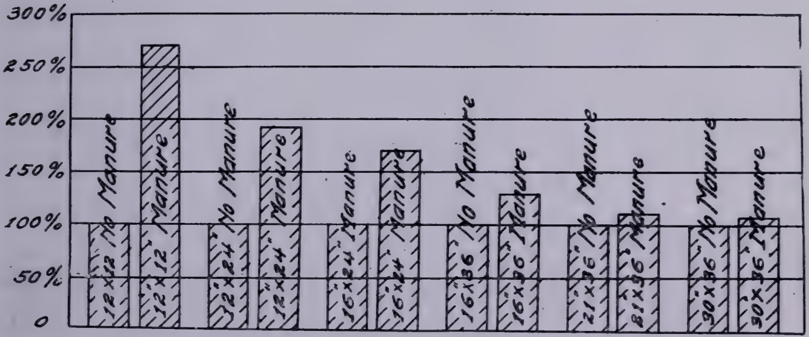

Chart IV.—Effect on total dry weight of plant from applying manure to potometers of different sizes. See Table 5.

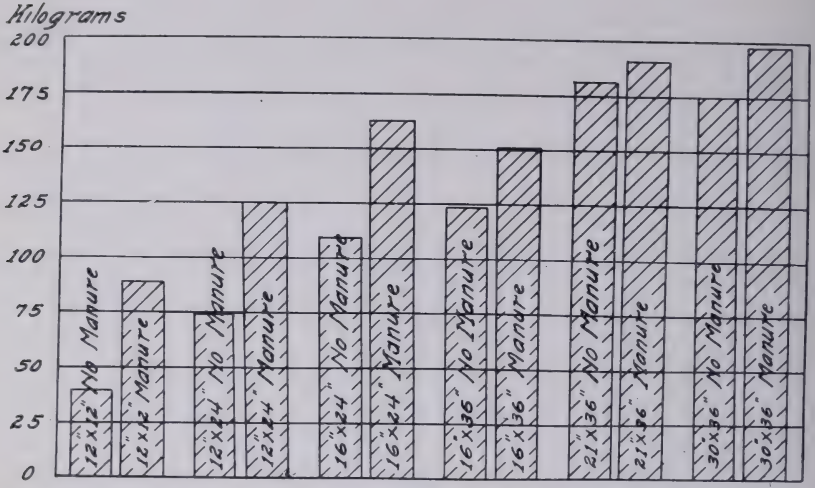

Chart V.—Effect of size of potometer upon the total amount of water transpired by one corn plant. 1914. See Table 7.

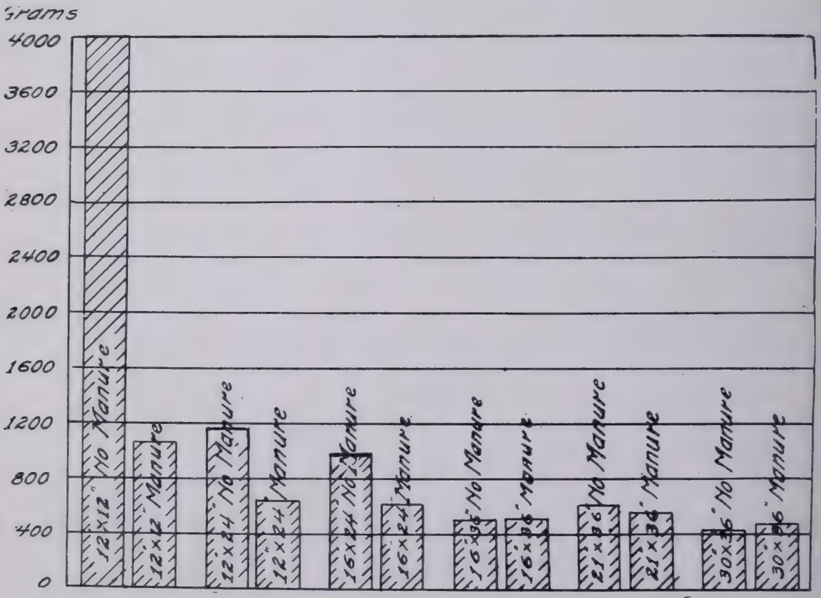

Chart VI.—Effect of size of potometer upon the amount of water used to produce one gram dry weight of ear corn. 1914. See Table 7.

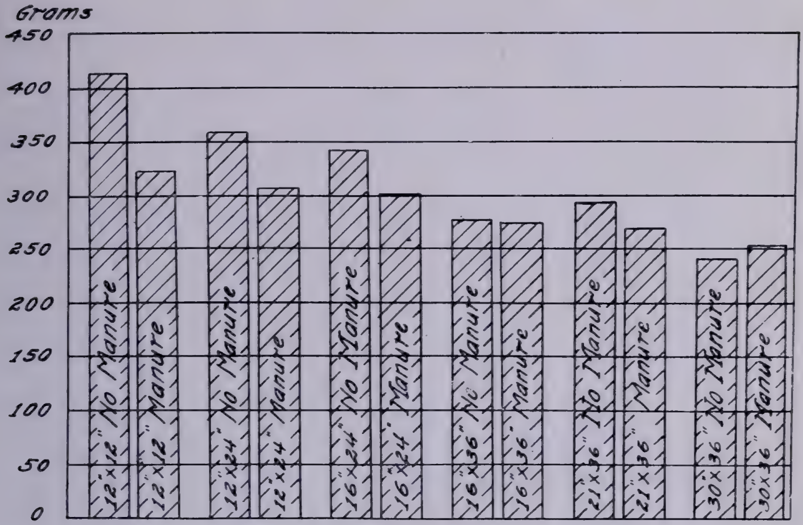

Chart VII.—Effect of size of potometer upon the amount of water required to produce one gram total dry matter with corn. 1914. See Table 7.

EFFECT OF EXPOSURE OF POTOMETER ON THE GROWTH AND WATER REQUIREMENTS OF CORN.[1]

As is rather customary in pot experiments, our potometers have been exposed to the surrounding atmospheric conditions rather than buried in the soil. This greatly facilitates weighing and handling, but subjects the soil contents to somewhat different temperatures than are normal under field conditions. Potometers exposed in this manner have been criticized by several investigators. Fortier, Hasselbring, Thom, and Willard and Humbert have surrounded their pots with a water jacket, for the purpose of reducing temperature fluctuations. In order to secure data concerning the effect of this exposure upon soil temperature, growth, and transpiration, the tests reported in Tables 9, 10, and 11 were made.

The subirrigation type of potometer was used and all were filled with fertile surface-loam soil equivalent to 239 pounds moisture-free soil, and 1.75 pounds moisture-free sheep manure was added. Eight potometers were fully exposed in the pit, and eight were buried in the soil in the field and connected by means of

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[1] References concerning the effect of the exposure of the potometer: King (1895), Leather (1911), Liebscher (1895), and Briggs and Shantz (1914)

TABLE 9.—*Effect of degree of exposure of potometer upon growth and water requirements of corn.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
POTOMETERS IN PIT FULLY EXPOSED TO ATMOSPHERE												
7	313	276	58	647	181.590	1,478	657.93	280.66	122.85	2.28	.88	126
52	205	320	48	573	154.480	1,315	482.75	269.60	117.48	2.29	1.56	115
75	225	352	51	628	181.610	1,190	515.94	289.20	152.60	1.90	1.56	110
110	158	273	40	471	119.670	928	438.35	254.10	128.96	1.97	1.73	94
20	219	284	50	553	140.380	1,324	494.29	253.89	106.03	2.39	1.30	118
39	227	329	52	608	165.550	1,635	503.19	272.30	101.28	2.69	1.45	121
78	193	287	52	532	137.570	1,454	479.34	258.60	94.62	2.73	1.49	120
97	226	179	44	449	132.990	1,248	742.96	296.20	106.58	2.78	.79	110
Average....	220.75	287.50	49.40	557.60	151.730	1,321.5	527.76	272.12	114.82	2.37	1.30	114
POTOMETERS BURIED IN THE SOIL												
117	271	248	60	579	154.280	1,978	622.09	266.45	78.00	3.42	.92	111
118	245	278	48	571	161.980	1,484	582.66	283.70	109.15	2.60	1.13	124
120	197	323	47	567	152.700	1,400	472.76	269.31	109.07	2.47	1.64	103
121	184	196	51	431	126.090	1,456	643.32	292.55	86.59	3.38	1.07	96
122	274	214	47	535	165.250	1,423	772.19	308.86	116.13	2.66	.78	116
124	250	287	52	589	155.940	1,579	543.34	264.72	98.76	2.68	1.15	110
Average....	236.80	257.70	50.80	545.30	152.707	1,553.0	592.58	280.04	98.30	2.85	1.10	110
POTOMETERS IN PIT SURROUNDED BY 4-INCH WATER JACKET												
25	292	298	60	650	184.900	1,833	620.47	284.46	100.87	2.82	1.02	126
34	229	264	40	533	145.260	1,188	550.23	272.53	122.27	2.23	1.15	103
83	209	347	49	605	143.580	1,197	413.78	237.32	119.95	1.98	1.66	112
92	306	263	53	622	176.740	1,470	672.02	284.15	120.23	2.36	.86	123
Average....	259.00	293.00	50.50	602.50	162.620	1,422.0	555.02	270.00	114.35	2.36	1.13	116

protected tubes with watering jars which stood in the pit. Four others were surrounded by a 4-inch water jacket, which was kept filled with water. The water jackets as used were not exactly what water-jacket advocates recommend in that they were not sunk in the ground, but rather stood on top of the floor of the pit. A buried water jacket would have kept the potometer temperature more nearly the same as the field soil, and in future tests of the method this will be provided for. The advantage of surrounding the potometer with a water jacket rather than filling soil around it is that it may facilitate occasional weighing.

TABLE 10.—*Summary of effect of degree of exposure of potometer upon growth and water requirements of corn. 1914.*

Exposure of potometers	Dry matter		Total water transpired	Transpiration per	
	Ear	Total		gram dry wt. of ear	gram total dry matter
(1)	*Grams* (2)	*Grams* (3)	*Kilos.* (4)	*Grams* (5)	*Grams* (6)
Potometers fully exposed in pit to atmosphere..............	287.5	557.6	151.7	527.8	272.1
Potometers buried in soil...............	257.7	545.3	152.7	592.6	280.0
Potometers in pit surrounded by 4-inch water jacket........	293.0	602.5	162.6	555.0	270.0

The exposed, buried, and water-jacket potometers in the cornfield respectively produced an average yield of 557.6, 545.30, and 602.5 grams of dry matter; transpired 151.7, 152.7, and 162.6 kilograms of water; and used 272.1, 280.0, and 270.0 grams of water per gram of dry matter. The differences obtained from exposed and buried potometers are not large, and it would appear that reliable comparative data may be secured from large exposed potometers.

The potometer soil temperatures were taken 15 inches below the surface both in the center and at a distance of 1 inch from the edge. The results are recorded in Table 11. The daily average soil temperatures of the exposed potometers was 4.1° F. higher than of those buried in the soil, which in turn were 2.4° F. warmer than the field soil at a depth of 1 foot. The water jacket raised the average temperature 0.5° F. The soil did not get quite as warm in the daytime but cooled off less at night. With 4.1

TABLE 11.—*Summary showing effect of degree of exposure of potometers upon their soil temperatures. (Average for 30 days, July 10 to August 11.)*

Time of temperature reading	Location in potometer of temp. reading	Potometer buried in soil	Potometer in water jacket in pit	Potometer fully exposed in pit	Soil in cornfield		Air temp. in shade
		Degrees F.	*Degrees F.*	*Degrees F.*	*Inches deep*	*Degrees F.*	*Degrees F.*
7:30 a. m....	Center....	77.1	81.2	79.3	12	75.6	....
	Edge......	77.4	80.5	77.4	24	73.7	....
	Average...	77.2	80.8	78.3	Average	74.6	73.2
1:30 p. m....	Center....	77.4	80.5	80.1	12	76.1	....
	Edge......	77.4	81.9	83.0	24	74.4	....
	Average...	77.4	81.2	81.5	Average	75.2	89.4
5:30 p. m....	Center....	77.4	83.5	83.1	12	76.1	....
	Edge......	77.7	84.7	86.5	24	74.4	....
	Average...	77.5	84.1	84.8	Average	75.2	88.2
Daily av. in center.......		77.3	81.7	80.8	Av. 12	75.9	....
Daily av. in edge........		77.5	82.4	82.3	Av. 24	74.2	....
Daily average............		77.4	82.0	81.5	....	75.0	83.6

degrees lower temperature, the buried potometers used 3 per cent more water per gram of dry matter than those fully exposed in the pit.

VARIATION IN RESULTS FROM SIMILAR POTOMETERS AND REDUCTION OF ERROR BY REPETITION.

Forty-eight standard potometers were planted to Hogue's Yellow Dent corn in 1912 and 80 potometers in 1913. The weight of moisture-free soil was 248 pounds in 1912 and 243 pounds in 1913. The potometers were filled with soil from a productive field taken to a depth of 6 inches and no additional fertilizer was added. The soil-moisture content was maintained constant by adding water to the jars at the base. The conditions were similar each year for all plants tested, and the variations between the different plants in any one year may be regarded as indicating the amount of experimental error to be expected between individual potometers due to individuality of the plants. The detailed data for 1912 for the individual potometers are given in Table 12. The potometers have been averaged in groups of four adjacent potometers to correspond to one of the regular experiments in which the effects of differences in soil moisture, soil fertility, or variety are compared. The 80 plants grown in 1913 and the ears harvested from them are shown in Figures 13 and 14.

The results from the 48 potometers of 1912 and the 80 potometers of 1913 have been compiled in Tables 13 to 21 so as to show the extreme variation and the coefficient of variability when single potometers are used and when grouped in sets of two and four each. Since variation varies with frequency, these coefficient of variability tables have been prepared so that the averages are for the same frequency, whether single potometers or the mean of two or four potometers is used.

The coefficients of variability for the two years may be summarized as in Table 22.

The data show a consistent reduction in the coefficient of variability as the number of potometers averaged together is increased. However, considerable variation still exists when four potometers are averaged together, and the data will serve to guard against attaching too much importance to very small differences in the experiments which follow.

The extreme variation between groups of four is also seen to be rather high, and this must be kept in mind when interpreting results.

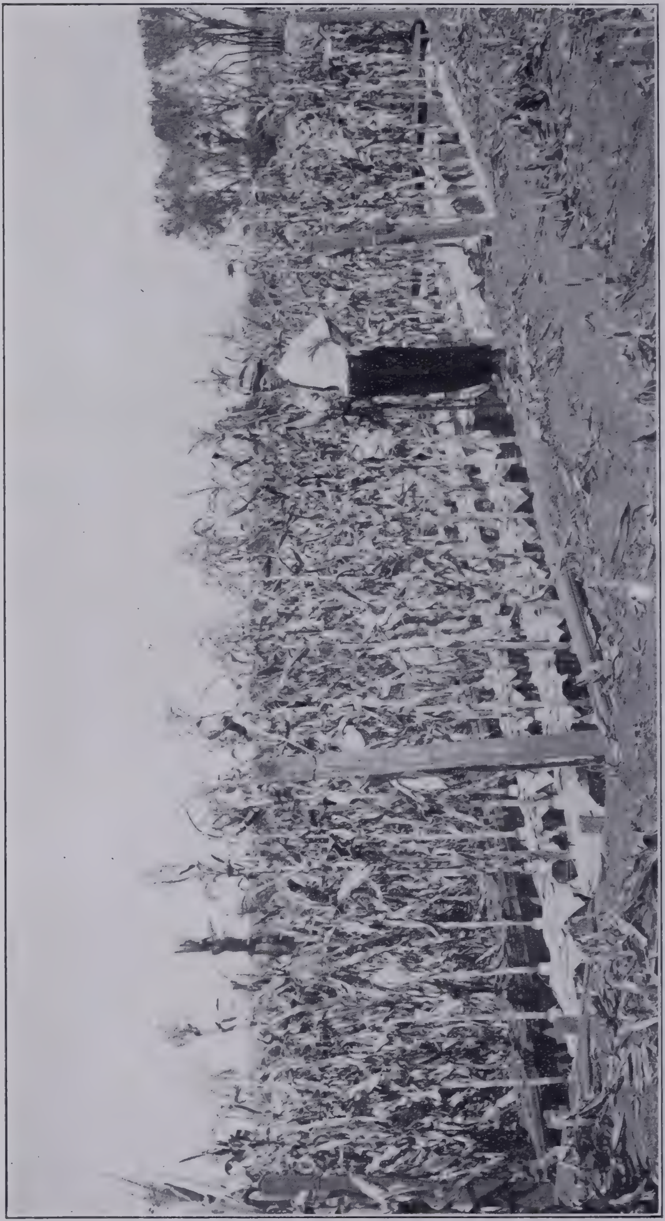

Fig. 13.—Mature plants grown in method study pit in 1913. All of the potometers in this pit were given identical treatment, and planted to seed from a single ear of Hogue's Yellow Dent corn for the purpose of studying variation. The field corn surrounding the potometers has been cut away in the foreground to facilitate taking the picture. See Tables 13 to 22.

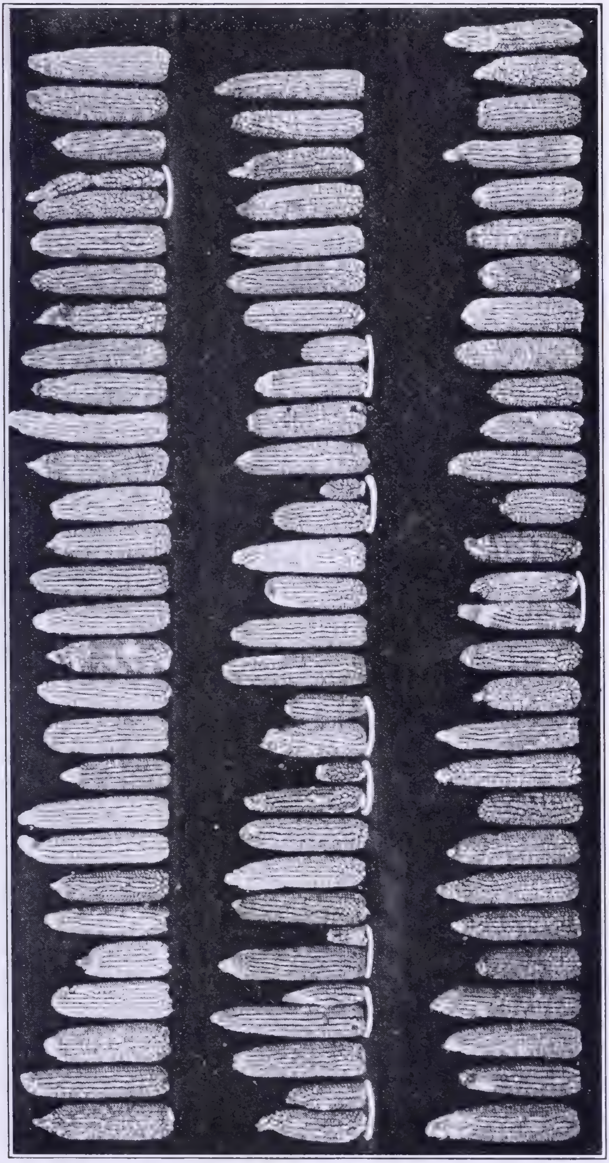

Fig. 14.—Corn ears grown on the 80 plants in the 1913 method study pit to determine approximately what variation between individuals may be expected to occur as a source of experimental error. See Tables 13 to 22.

TABLE 12.—*Results from 48 plants grown in potometers in 1912 to study variation in water requirements.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
	Grams	*Grams*	*Grams*	*Grams*	*Kilograms*	*Sq. in.*	*Grams*	*Grams*	*Grams*	*Sq. in.*		*Inches*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	118	163	16	297	90.362	673	554.37	304.25	134.27	2.27	1.38	93
2	178	198	25	401	116.140	891	586.57	289.63	130.35	2.22	1.11	105
3	136	247	35	418	106.093	861	429.53	253.81	123.22	2.06	1.82	93
4	118	231	28	377	104.145	840	450.84	276.25	123.98	2.23	1.96	96
Average....	137.50	209.75	26.00	373.25	104.185	816.25	469.70	279.14	127.64	2.19	1.53	97
5	139	245	29	413	112.937	845	460.97	273.46	133.65	2.05	1.76	99
6	170	284	23	477	116.752	918	411.10	244.76	127.18	1.92	1.67	102
7	117	235	21	373	95.886	636	408.03	257.06	150.76	1.71	2.01	81
8	100	190	9	299	74.503	600	392.12	249.17	124.17	2.01	1.90	86
Average....	131.50	238.50	20.50	390.50	100.0195	749.75	419.37	256.13	133.40	1.92	1.81	92
9	162	259	31	452	125.736	818	485.47	278.18	153.71	1.81	1.60	107
10	141	284	27	452	114.733	764	404.00	253.83	150.17	1.69	2.01	107
11	135	234	25	394	98.850	654	422.44	250.89	151.15	1.66	1.73	98
12	129	252	33	414	114.104	795	452.79	275.61	143.53	1.92	1.95	88
Average....	141.75	257.25	29.00	428.00	113.356	757.75	440.65	264.85	149.60	1.77	1.81	100
13	131	238	27	396	121.076	689	508.72	305.75	175.73	1.74	1.82	90
14	175	251	38	464	116.569	852	464.42	251.23	136.82	1.84	1.43	98
15	136	225	21	382	110.909	822	492.93	290.34	134.93	2.15	1.65	93
16	127	242	27	396	93.236	865	385.27	235.44	107.79	2.18	1.91	85
Average....	142.25	239.00	28.25	409.50	110.448	807.00	462.13	269.71	136.86	1.97	1.68	91
17	151	233	35	419	103.966	837	446.21	248.13	124.21	2.00	1.54	99
18	135	175	16	326	92.560	656	528.91	283.92	141.11	2.01	1.30	110
19	135	245	21	401	94.018	776	383.75	234.46	121.16	1.94	1.81	96
20	155	272	38	465	107.238	983	394.26	230.62	109.09	2.11	1.75	108
Average....	144.00	231.25	27.50	402.75	99.446	813.00	430.04	246.92	122.32	2.02	1.61	103

TABLE 12 CONTINUED.—*Results from 48 plants grown in potometers in 1912 to study variation in water requirements.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
	Grams	*Grams*	*Grams*	*Grams*	*Kilograms*	*Grams*	*Grams*	*Grams*	*Grams*	*Sq. in.*		*Inches*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
21	99	217	30	346	78.243	729	360.57	226.14	107.33	2.11	2.19	79
22	145	242	30	417	100.064	819	413.48	239.96	122.18	1.96	1.67	81
23	171	279	28	478	148.130	962	530.93	309.90	153.98	2.01	1.63	100
24	148	228	30	406	120.265	805	527.48	296.22	149.40	1.98	1.54	103
Average....	140.75	241.50	29.50	411.75	111.676	828.75	462.43	271.23	134.75	2.01	1.72	91
25	164	222	25	411	106.247	701	478.59	258.51	151.56	1.71	1.35	102
26	159	223	27	409	100.193	828	449.30	244.97	121.01	2.02	1.40	93
27	163	276	31	470	112.346	856	407.05	239.03	131.26	1.82	1.69	108
28	132	220	21	373	91.302	646	415.01	244.83	141.33	1.73	1.67	98
Average....	154.50	235.25	26	415.75	102.522	757.75	435.81	246.60	135.30	1.82	1.52	100
29	164	242	25	431	110.704	792	457.45	256.85	139.78	1.84	1.48	94
30	134	246	29	409	123.948	829	503.85	303.05	149.52	2.03	1.84	97
31	123	233	31	387	85.107	671	365.27	219.91	126.84	1.73	1.89	79
32	171	227	37	435	103.292	783	455.03	237.45	131.92	1.80	1.33	86
Average....	148.00	237.00	30.50	415.50	105.763	768.75	446.26	254.54	137.58	1.85	1.60	89
33	182	194	30	406	118.377	847	610.19	291.57	139.76	2.09	1.07	102
34	196	190	35	421	114.734	1,039	603.86	272.53	110.43	2.47	.97	94
35	126	270	26	422	104.227	909	386.03	246.98	114.66	2.15	2.14	109
36	188	253	38	479	114.380	1,132	452.09	238.79	101.04	2.36	1.35	109
Average....	173.00	226.75	32.25	432.00	112.930	981.75	498.04	261.41	115.04	2.27	1.31	103
37	147	193	24	364	112.202	816	581.36	308.25	137.50	2.24	1.31	108
38	134	261	31	426	108.801	894	416.86	255.40	121.70	2.10	1.95	93
39	135	231	31	397	100.657	854	435.74	253.53	117.87	2.15	1.71	97
40	95	163	20	278	67.595	540	414.69	243.15	125.18	1.94	1.72	72
Average....	127.75	212.00	26.50	366.25	97.314	776.00	459.03	265.70	125.40	2.12	1.66	92

TABLE 12 CONTINUED.—*Results from 48 plants grown in potometers in 1912 to study variation in water requirements.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
	Grams	*Grams*	*Grams*	*Grams*	*Kilograms*	*Sq. in.*	*Grams*	*Grams*	*Grams*	*Sq. in.*		*Inches*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
41	150	258	29	437	116.485	843	451.48	266.56	138.18	1.93	1.72	78
42	145	245	28	418	111.181	739	453.81	265.98	150.45	1.77	1.69	97
43	167	200	31	398	103.422	790	517.11	259.85	130.91	1.98	1.20	98
44	158	235	32	425	89.354	838	380.23	210.24	106.63	1.97	1.49	90
Average....	155.00	234.50	30.00	419.50	105.111	802.50	448.23	250.56	130.98	1.91	1.51	91
45	125	234	18	377	95.080	677	406.32	252.20	140.44	1.80	1.87	87
46	155	236	24	415	117.794	950	499.13	283.84	123.99	2.29	1.52	99
47	147	255	28	430	110.219	818	432.23	256.32	134.74	1.90	1.73	81
48	166	270	33	469	120.249	844	445.45	256.35	142.48	1.80	1.63	95
Average....	148.25	248.75	25.75	422.75	110.834	822.25	445.56	262.18	134.79	1.95	1.68	90

TABLE 13.—*Dry weight of stalks in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean dry wt. of stalk	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
YEAR 1912						
48 single potometers	a 12	136.92	100 —178	17.57	23.31	17.03
	b 12	142.33	99 —175	15.17	20.93	14.71
	c 12	158.50	123 —196	19.83	23.60	14.89
	d 12	143.67	95 —167	14.77	18.99	13.22
Average		145.35	104.25—179.00	16.83	21.71	14.96
Two adjacent potometers in a group	a 12	139.63	108.50—159.50	12.85	14.75	10.56
	b 12	151.08	115.00—189.00	11.85	19.36	12.82
Average		145.35	111.75—174.25	12.35	17.05	11.69
Four adjacent potometers in a group	12	145.35	127.75—173.00	8.66	11.42	7.86
YEAR 1913						
80 single potometers	a 20	153.90	122 —197	17.00	19.93	12.95
	b 20	150.20	113 —180	15.16	18.26	12.16
	c 20	146.00	120 —183	14.30	18.51	12.68
	d 20	152.20	98 —201	18.28	23.32	15.32
Average		150.58	113.25—190.25	16.19	20.01	13.28
Two adjacent potometers in a group	a 20	152.05	126.5 —183.5	10.31	13.35	8.78
	b 20	149.10	111.0 —183.5	14.17	17.61	11.81
Average		150.58	118.75—183.50	12.24	15.48	10.29
Four adjacent potometers in a group	20	150.58	132.50—166.25	7.90	9.38	6.23

TABLE 14.—*Dry weight of ear in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean dry wt. of ear	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	235.17	163 —284	26.67	34.77	14.78
	b 12	237.25	175 —279	18.04	25.47	10.74
	c 12	233.00	190 —276	20.33	25.27	10.85
	d 12	231.75	163 —270	23.33	30.27	13.06
Average		234.29	172.75—277.25	22.09	28.95	12.36
Two adjacent potometers in a group	a 12	236.21	180.5 —271.5	20.17	25.36	10.74
	b 12	232.38	192.0 —262.5	18.04	21.88	9.41
Average		234.29	186.25—267.00	19.11	23.62	10.08
Four adjacent potometers in a group	12	234.29	209.75—257.25	9.57	12.92	5.51
		YEAR 1913				
80 single potometers	a 20	179.90	125 —236	20.82	27.12	14.08
	b 20	184.70	127 —216	21.29	26.30	14.24
	c 20	169.70	111 —210	19.90	23.64	13.93
	d 20	159.80	109 —222	27.40	31.63	19.79
Average		173.53	118.00—221.00	22.35	27.17	15.76
Two adjacent potometers in a group	a 20	182.30	142 —211.5	16.43	18.71	10.26
	b 20	164.75	122 —200.0	16.10	19.89	12.08
Average		173.53	132.00—205.75	16.27	19.30	11.17
Four adjacent potometers in a group	20	173.53	146.50—202.75	11.30	14.83	8.55

TABLE 15.—*Dry weight of leaves in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean dry wt. of leaves	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	25.17	9 —35	5.33	6.99	27.76
	b 12	28.42	16 —38	5.08	6.47	22.78
	c 12	29.58	21 —38	4.08	4.96	16.76
	d 12	27.42	18 —33	3.94	4.66	17.07
Average		27.65	16.00—36.00	4.61	5.77	21.09
Two adjacent potometers in a group	a 12	26.79	15 —32.5	3.83	4.79	17.89
	b 12	28.50	21 —34.0	3.00	3.57	12.51
Average		27.65	18.00—33.25	3.41	4.18	15.20
Four adjacent potometers in a group	12	27.65	20.50—32.25	2.27	2.92	10.54
		YEAR 1913				
80 single potometers	a 20	50.00	36 —67	5.90	7.24	14.48
	b 20	46.55	37 —55	4.75	5.32	11.41
	c 20	47.65	35 —58	5.22	6.06	12.72
	d 20	47.90	23 —60	7.62	9.50	19.83
Average		48.03	32.75—60.00	5.87	7.03	14.61
Two adjacent potometers in a group	a 20	48.28	40.5 —59.0	3.73	4.67	9.66
	b 20	47.78	30.5 —57.0	4.80	6.16	12.89
Average		48.03	35.50—58.00	4.26	5.41	11.28
Four adjacent potometers in a group	20	48.03	37.75—56.25	3.25	4.38	9.12

TABLE 16.—*Total dry weight of plant in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean total dry wt. of plant	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	397.25	297 —477	41.04	53.26	13.41
	b 12	408.00	326 —478	33.83	43.86	10.75
	c 12	421.08	373 —479	21.93	29.06	6.90
	d 12	402.83	278 —469	33.36	46.10	11.47
Average	....	407.29	318.50—475.75	32.54	43.07	10.63
Two adjacent potometers in a group	a 12	402.63	336.00—452.00	31.71	36.50	9.07
	b 12	411.96	337.50—450.50	18.49	27.97	6.79
Average	....	407.29	337.75—451.25	25.10	32.23	7.93
Four adjacent potometers in a group	12	407.29	366.25—432.00	16.07	19.87	4.88
		YEAR 1913				
80 single potometers	a 20	383.80	328 —463	25.28	34.02	8.86
	b 20	381.45	318 —437	25.21	29.32	7.69
	c 20	363.35	311 —446	23.62	31.04	8.54
	d 20	359.90	248 —457	35.73	47.91	13.31
Average	....	372.13	301.25—450.75	27.46	35.57	9.60
Two adjacent potometers in a group	a 20	382.63	335.50—436.00	19.04	24.57	6.42
	b 20	361.63	269.00—431.50	24.96	34.18	9.45
Average	....	372.13	302.15—433.75	22.00	29.37	7.94
Four adjacent potometers in a group	20	372.15	323.00—401.00	14.84	18.74	5.04

TABLE 17.—*Leaf-area per plant in similar potometers planted with Hogue's Yellow Dent corn.*

	Number of groups	Mean leaf-area per plant	Extreme variation	Average deviation	Standard deviation	Coefficient of variabilty
		Sq. in.	*Square inches*	*Sq. in.*	*Sq. in.*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	774.58	600 — 918	90.99	103.19	13.32
	b 12	816.25	656 — 983	71.04	93.28	11.43
	c 12	836.08	646 —1,132	100.45	135.73	16.23
	d 12	800.25	540 — 950	75.83	103.62	12.95
Average		806.79	610.50— 995.75	84.58	108.95	13.48
Two adjacent potometers in a group	a 12	795.42	618 — 883.5	60.24	75.15	9.45
	b 12	818.17	697 —1,020.5	61.14	86.25	10.54
Average		806.79	657.50— 952.00	60.69	80.70	10.00
Four adjacent potometers in a group	12	806.79	749.75— 918.75	38.04	59.13	7.33
		YEAR 1913				
80 single potometers	a 20	1,108.95	791 —1,521	144.64	185.00	16.68
	b 20	1,025.80	815 —1,366	123.00	147.57	14.39
	c 20	1,070.30	850 —1,351	105.70	131.84	12.32
	d 20	1,074.05	730 —1,356	128.46	153.26	14.27
Average		1,069.78	796.50—1,398.50	125.45	154.42	14.41
Two adjacent potometers in a group	a 20	1,067.38	891 —1,312.5	108.91	129.71	12.15
	b 20	1,072.18	882 —1,310.0	83.14	108.60	10.13
Average		1,069.78	886.50—1,311.25	96.03	119.15	11.14
Four adjacent potometers in a group	20	1,069.78	945.75—1,232.75	55.77	67.77	6.33

TABLE 18.—*Total transpiration per plant in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean total water used per plant	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Kilograms	*Kilograms*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	105.85	74.50—125.74	10.92	13.52	12.77
	b 12	107.19	78.24—148.13	13.50	17.61	16.43
	c 12	107.07	85.11—123.95	8.68	10.67	9.97
	d 12	104.42	67.60—120.25	11.00	14.20	13.60
Average		106.13	76.36—129.52	11.03	14.00	13.19
Two adjacent potometers in a group	a 12	106.52	85.20—134.20	10.34	13.05	12.25
	b 12	105.75	84.13—117.33	8.15	9.79	9.26
Average		106.13	84.66—125.76	9.25	11.42	10.75
Four adjacent potometers in a group	12	106.13	97.31—113.36	4.76	5.38	5.07
		YEAR 1913				
80 single potometers	a 20	166.00	144.93—189.03	9.87	12.36	7.45
	b 20	164.60	143.95—186.47	9.31	11.56	7.03
	c 20	163.30	139.24—185.06	10.61	12.72	7.79
	d 20	166.33	128.54—186.87	11.05	14.02	8.43
Average		165.06	139.16—186.86	10.21	12.67	7.67
Two adjacent potometers in a group	a 20	165.35	152.29—181.93	7.03	8.08	4.89
	b 20	164.81	137.39—177.88	8.59	10.34	6.27
Average		165.08	144.84—179.91	7.81	9.21	5.58
Four adjacent potometers in a group	20	165.06	152.28—175.75	3.88	5.40	3.28

TABLE 19.—*Water used per gram of dry weight of ear in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean water used per gr. dry wt. of ear	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	454.85	392.12— 586.57	44.66	58.14	12.78
	b 12	453.08	383.75— 530.93	55.82	61.37	13.54
	c 12	465.31	365.27— 610.19	55.87	73.41	15.75
	d 12	452.87	380.23— 581.36	39.99	53.04	11.71
Average		456.53	380.34— 577.26	49.09	61.49	13.45
Two adjacent potometers in a group	a 12	453.97	387.03— 570.47	42.98	53.32	11.75
	b 12	459.09	410.15— 607.03	35.73	51.67	11.25
Average		456.53	398.59— 588.75	39.36	52.49	11.50
Four adjacent potometers in a group	12	456.53	418.06— 513.05	19.81	26.35	5.77
		YEAR 1913				
80 single potometers	a 20	941.99	738.06—1,211.11	120.13	142.15	15.09
	b 20	911.28	719.98—1,304.72	121.51	154.82	16.99
	c 20	975.49	816.24—1,254.43	91.41	110.52	11.33
	d 20	1,074.24	805.37—1,523.71	161.58	191.37	17.81
Average		975.75	769.91—1,323.49	123.66	149.72	15.31
Two adjacent potometers in a group	a 20	926.64	739.25—1,141.59	77.54	92.94	10.03
	b 20	1,024.87	826.13—1,312.65	90.40	118.39	11.55
Average		975.75	782.69—1,227.12	83.97	105.67	10.79
Four adjacent potometers in a group	20	975.75	811.45—1,123.96	72.21	87.92	9.01

TABLE 20.—*Water transpired per gram of dry weight of crop in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean water used per gr. total dry wt. of plant	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	267.24	244.76—304.25	15.65	17.66	6.6
	b 12	262.68	226.14—309.90	28.79	30.53	11.62
	c 12	254.54	219.91—303.05	18.30	22.90	9.00
	d 12	259.31	210.24—308.25	14.66	22.14	8.54
Average		260.94	225.26—306.36	19.35	23.31	8.94
Two adjacent potometers in a group	a 12	264.92	232.54—303.06	14.26	20.23	7.63
	b 12	256.92	228.68—282.05	15.59	17.78	6.92
Average		260.92	230.61—292.56	14.93	19.00	7.28
Four adjacent potometers in a group	12	260.92	246.60—279.14	8.16	9.69	3.72
		YEAR 1913				
80 single potometers	a 20	434.03	379.05—481.83	22.63	28.41	6.55
	b 20	432.44	391.88—493.74	18.66	25.04	5.79
	c 20	450.29	398.95—488.84	18.16	23.26	5.17
	d 20	466.87	358.67—531.00	33.12	42.57	9.12
Average		445.91	382.14—498.85	23.14	29.82	6.66
Two adjacent potometers in a group	a 20	433.24	394.56—471.54	14.27	19.36	4.47
	b 20	458.59	379.67—512.34	21.27	30.05	6.55
Average		445.92	387.12—491.94	17.77	24.71	5.51
Four adjacent potometers in a group	20	445.92	412.92—487.47	17.89	20.45	4.60

TABLE 21.—*Water used per square inch of leaf-area in similar potometers planted with Hogue's Yellow Dent corn.*

Classification	Number of groups	Mean water used per sq. in. leaf-area	Extreme variation	Average deviation	Standard deviation	Coefficient of variability
		Grams	*Grams*	*Grams*	*Grams*	*Per cent*
		YEAR 1912				
48 single potometers	a 12	137.18	123.22—153.71	10.57	11.43	8.33
	b 12	131.98	107.33—175.73	16.68	20.02	15.17
	c 12	129.93	101.04—151.56	12.69	15.21	11.71
	d 12	130.84	106.63—150.45	9.80	11.70	8.94
Average		132.48	109.56—157.86	12.43	14.59	11.04
Two adjacent potometers in a group	a 12	134.58	114.76—156.28	11.97	13.93	10.35
	b 12	130.39	107.85—144.65	8.35	10.37	7.95
Average		132.48	111.31—150.47	10.16	12.15	9.15
Four adjacent potometers in a group	12	132.48	116.48—149.64	6.16	8.06	6.09
		YEAR 1913				
80 single potometers	a 20	153.02	116.37—194.21	18.32	22.53	14.73
	b 20	163.42	121.76—221.99	19.33	24.01	14.69
	c 20	154.31	122.92—188.41	14.76	17.86	11.58
	d 20	156.99	128.40—191.28	17.01	18.75	11.94
Average		156.94	122.36—198.97	17.35	20.79	13.23
Two adjacent potometers in a group	a 20	158.22	126.78—190.38	14.85	17.90	11.31
	b 20	155.65	129.16—182.36	12.95	15.31	9.83
Average		156.94	127.97—186.37	13.90	16.60	10.57
Four adjacent potometers in a group	20	156.94	138.35—176.27	7.57	9.12	5.81

TABLE 22.—*Summary showing coefficients of variability for 48 similar potometers in 1912 and 80 potometers in 1913. Compiled from Tables 13 to 21.*

Character	Coefficients of variability					
	1912			1913		
	Single potometer	Two in a group	Four in a group	Single potometer	Two in a group	Four in a group
1. Dry weight of stalk (grams)	14.96	11.69	7.86	13.28	10.29	6.23
2. Dry weight of ear (grams)	12.36	10.08	5.51	15.76	11.17	8.55
3. Dry weight of leaves (grams)	21.09	15.20	10.54	14.61	11.28	9.12
4. Total dry weight of plant (grams)	10.63	7.93	4.88	9.60	7.94	5.04
5. Total water transpired (kilograms)	13.19	10.75	5.07	7.67	5.58	3.28
6. Total leaf-area per plant (square inches)	13.48	10.00	7.33	14.41	11.14	6.33
7. Water used per gram dry wt. of ear (grams)	13.45	11.50	5.77	15.31	10.79	9.01
8. Water used per gram dry wt. of plant (grams)	8.94	7.28	3.72	6.66	5.51	4.60
9. Water used per square inch leaf-area (grams)	11.04	9.15	6.09	13.23	10.57	5.81

THE RELATION OF CLIMATE TO TRANSPIRATION.[1]

HOURLY TRANSPIRATION AND EVAPORATION IN RELATION TO CLIMATIC FACTORS.

Records have been secured during two years, 1910 and 1914, relative to the amount of water transpired by a corn plant and the amount evaporated from a free water surface during consecutive hours of the day in a cornfield. A record of the accompanying climatic factors was taken by means of self-recording instruments in the cornfield. The facilities and methods for obtaining these records are shown in Figure 5, p. 47.

The United States Weather Bureau has installed at the Nebraska Experiment Station a Marvin pyrheliometer and a Callendar recording pyrheliometer, so that beginning with 1915 solar radiation records will be available for correlation with transpiration and evaporation in addition to those weather records taken heretofore.

The transpiration data were secured from plants standing undisturbed on platform scales thruout the tests. The scales were read at the end of each hour between 7 a. m. and 8 p. m., and the hourly transpiration was determined by loss in weight. Only the total transpiration and evaporation were determined for the night, but the weather factors were being taken continually. The test was made after the plants had acquired their maximum leaf-area. In 1910 the soil contained 60 per cent and in 1914 ,70 per cent of its water-holding capacity.

In 1910 the evaporation data were secured by averaging the losses from five Livingston porous clay cups at an elevation midway between the base and tip of the plant. In 1914 a shallow free water surface was used, 1.5 inches deep and of 36 square-inch surface area, in which the water was restored by weight to the jar each day to one-half inch below the top. A shallow body of water has been found to respond more readily to changing conditions than a deeper body. The data are given in Tables 23 and 24, and in Charts VIII and IX.

The 1914 data are an average for 30 days between July 14 and August 22 (weighings were not made on rainy days), while the 1910 data are the average for only nine days. The former, therefore, are more representative because of a greater duration.

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[1] References concerning the relation of transpiration to climatic factors: Briggs and Shantz (1913, 1914), Fittbogen (1873), Hasselbring (1914), Hellriegel (1883), Heinrich (1894), Kiesselbach and Montgomery (1911), Kiesselbach (1910), King (1905), Leather (1910, 1911), Montgomery and Kiesselbach (1912), Pfeiffer et al. (1912), Seelhorst and Müther (1905), Sorauer (1880), and Wollny (1877).

TABLE 23.—*Summary of transpiration, free-water-surface evaporation, and weather factors during successive hours of the day and night. (Only the total water losses were obtained for the night.) 1910.*[1]

Hour ending	Water transpired from 1 plant	Av. water evaporated from 5 clay cup evaporimeters	Mean temperature	Mean relative humidity	Wind velocity
(1)	(2) *Grams*	(3) *Grams*	(4) *Degrees F.*	(5) *Per cent*	(6) *Miles*
NIGHT					
8 p. m.	....	....	75.3	55.8	1.61
9 "	....	....	71.9	64.2	1.56
10 "	....	....	67.8	71.1	2.00
11 "	....	....	66.9	75.1	2.17
12 "	....	....	63.9	80.2	3.11
1 a. m.	....	....	62.0	82.0	2.22
2 "	....	....	61.2	83.0	1.47
3 "	....	....	60.1	84.1	1.67
4 "	....	....	59.2	84.6	1.22
5 "	....	....	58.6	85.7	1.22
6 "	....	....	58.2	85.9	1.39
7 "	....	....	60.1	86.0	2.00
Av. for night.....	17	0.44	63.8	78.1	1.80
DAY					
8 a. m.	78	1.82	63.9	78.8	3.85
9 "	121	2.40	69.1	68.7	5.24
10 "	186	4.02	74.4	58.3	5.76
11 "	246	4.59	78.3	50.3	6.14
12 "	261	5.60	81.2	45.9	6.54
1 p. m.	305	5.71	83.0	42.3	7.66
2 "	349	6.37	84.1	40.3	7.56
3 "	327	5.59	84.6	39.0	7.68
4 "	271	5.83	84.6	38.9	7.60
5 "	227	4.39	83.9	39.4	6.99
6 "	203	3.88	82.9	40.8	6.00
7 "	108	3.46	80.6	44.6	3.72
Av. for day......	223.5	4.47	79.2	48.9	6.23

[1] From Kiesselbach and Montgomery (1911).

The slight inconsistencies in 1910 are doubtless due in part to the short duration.

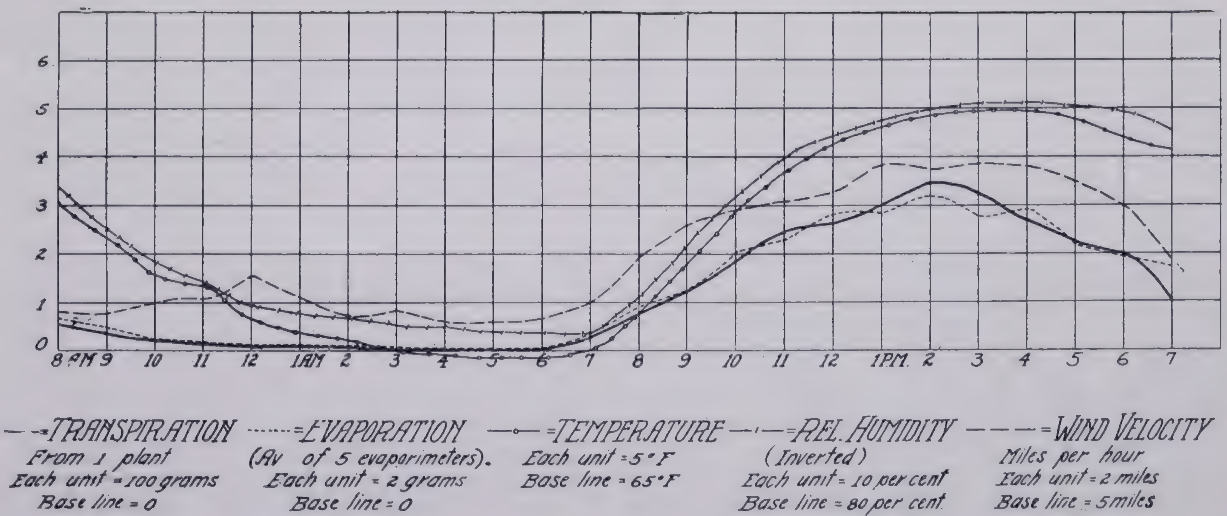
Altho only the total water loss was obtained for the night, the amount has been arbitrarily distributed in the charts thruout the night hours in order to give an approximate graphic comparison with the day loss.

During both years, the maximum transpiration and evapora-

TABLE 24.—*Summary of transpiration, free-water-surface evaporation, and weather factors during successive hours of the day and night. (Only the total water losses were obtained for the night. Average for 30 days during July 14 to August 22, 1914.)*

Hour ending	Water transpired from one plant (av. 30 days)	Water evaporated from 36 sq. in. free water surface (av. 30 days)	Mean temperature (av. 30 days)	Mean relative humidity (av. 30 days)	Mean wind velocity (av. 30 days)
(1)	(2)	(3)	(4)	(5)	(6)
Night	*Grams*	*Grams*	*Degrees F.*	*Per cent*	*Miles*
9 p. m.			79.1	70.2	6.2
10 "			77.0	75.1	6.8
11 "			75.6	76.8	7.3
12 "			74.5	79.4	7.1
1 a. m.			73.1	80.6	6.5
2 "			72.3	82.2	6.0
3 "			71.2	84.0	6.2
4 "			70.5	86.1	5.8
5 "			69.7	86.8	5.9
6 "			68.6	88.5	5.4
7 "			69.4	87.2	5.2
Av. for night...	15.8	2.32	72.8	81.5	6.2
DAY					
8 a. m.	84	4.8	73.6	80.2	6.0
9 "	111	7.7	77.9	72.8	6.9
10 "	167	11.6	81.7	67.1	8.0
11 "	215	15.0	84.8	62.7	8.2
12 "	279	19.2	87.5	58.5	8.7
1 p. m.	329	23.7	89.5	55.3	8.9
2 "	356	24.5	90.8	52.7	9.4
3 "	354	23.8	91.2	51.6	9.2
4 "	343	22.2	91.0	50.4	9.0
5 "	294	18.5	89.9	51.1	8.5
6 "	217	14.1	88.2	52.6	8.3
7 "	132	10.2	85.1	58.1	7.2
8 "	64	6.4	81.7	64.5	6.7
Av. for day....	226.5	15.5	85.6	59.8	8.1

tion rates occurred at the same hour—2 p. m. There is a rather long interval, approximately 1:00 p. m. to 4:00 p. m., during which the rate of loss is rather constant. As a whole, the water losses follow fairly regularly the natural sequence of the climatic changes. Transpiration or evaporation from the plant and the evaporation from a free water surface respond as nearly alike to changes in the climatic conditions during the day as one could expect from evaporating surfaces so dissimilar.



Char VIII.—Hourly variation in transpiration, evaporation, and climatic factors. Average for 9 days in August, 1910. (Graph of Table 23.)

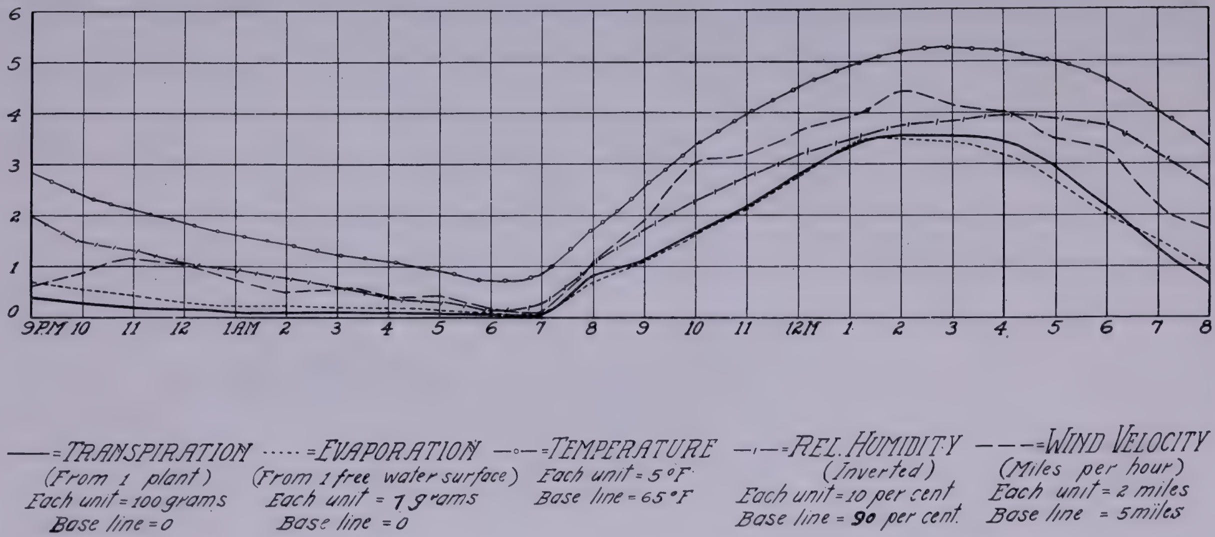


Chart IX.—Hourly variation in transpiration, evaporation, and climatic factors. Average for 30 days in July and August, 1914. (Graph of Table 24.)

In Table 25 the per cent increase or decrease from hour to hour in the transpiration and evaporation rate together with the accompanying fall or rise in the climatic factors is given for 1914. (The data are compiled from Table 24.) To illustrate: The average transpiration for the hour ending at 9 a. m. was 32 per cent greater than for the hour ending at 8 a. m. The transpiration from 9 to 10 a. m. was 50 per cent higher than that from 8 to 9 a. m., and so on. This table shows the actual amount of change in the climatic conditions from hour to hour and the resultant effect upon the amount of transpiration and evaporation.

TABLE 25.—*The data of Table 24 are here so calculated as to show the per cent increase or decrease in the transpiration and evaporation rates for each hour of the day over those of the preceding hour. The actual hourly increase or decrease in the weather factors is also given. Average for 30 days between July 14 and August 22, 1914.*

Hour ending	Per cent increase or decrease in transpiration over previous hour	Per cent increase or decrease in evaporation over previous hour	Rise or fall in temperature over previous hour	Rise or fall in relative humidity over previous hour	Rise or fall in wind velocity over previous hour
	Per cent	*Per cent*	*Degrees F.*	*Per cent*	*Miles*
(1)	(2)	(3)	(4)	(5)	(6)
9 a. m.	+32	+60	+4.3	—7.4	+ .9
10 "	+50	+51	+3.8	—5.7	+1.1
11 "	+29	+29	+3.1	—4.4	+ .2
12 "	+30	+28	+2.7	—4.2	+ .5
1 p. m.	+18	+23	+2.0	—3.2	+ .2
2 "	+ 8	+ 3	+1.3	—2.6	+ .5
3 "	— 1	— 3	+ .4	—1.1	— .2
4 "	— 3	— 7	— .2	—1.2	— .2
5 "	—14	—17	—1.1	+ .7	— .5
6 "	—26	—24	—1.7	+1.5	— .2
7 "	—39	—28	—3.1	+5.5	—1.1
8 "	—52	—37	—3.4	+6.4	—.5

From this table we can make the following deductions:

1. During that part of the day when the transpiration rate was increasing (7 a. m. to 2 p. m.) there was an actual average increase from hour to hour in:

Transpiration (per cent)	28.00
Evaporation (per cent)	32.00
Temperature (degrees F.)	2.90
Relative humidity (per cent decrease)	4.60
Wind velocity (miles per hour)	.60

2. During that part of the day when the transpiration decreased hourly (2 p. m. to 8 p. m.) there was an actual average decrease from hour to hour in:

Transpiration (per cent)	22.50
Evaporation (per cent)	20.00
Temperature (degrees F.)	1.50
Relative humidity (per cent increase)	2.00
Wind velocity (miles per hour)	.45

3. Averaging together the hourly differences thruout the 13 hours of the day regardless of whether plus or minus, we have as an hourly average for the day the following changes:

Transpiration (per cent)	25.00
Evaporation (per cent)	26.00
Temperature (degrees F.)	2.30
Relative humidity (per cent)	3.70
Wind velocity (miles per hour)	.50

4. As an average for the 13 daylight hours (7 a. m. to 8 p. m.) a 10 per cent change in the transpiration rate is accompanied by the following changes:

Transpiration (per cent)	10.00
Evaporation (per cent)	10.40
Temperature (degrees F.)	.90
Relative humidity (per cent)	1.50
Wind velocity (miles per hour)	.20

RELATIVE DAY AND NIGHT TRANSPIRATION AND EVAPORATION IN RELATION TO CLIMATIC FACTORS.

Table 26 is summarized from Tables 23 and 24, which show the hourly transpiration and evaporation rates for periods in 1910 and 1911 during which the plants were full grown and the leaf-area remained rather constant. The 24 hours were arbitrarily divided into 12 hours each for day and night in 1910, and in 1914 the night included 11 hours and the day 13 hours.

It is very interesting to note that as an average for the two years the average hourly night transpiration amounted to only 7.5 per cent of the hourly day loss. The corresponding difference in climatic factors is summed up as follows: The night temperature was 14.1° F. cooler, the relative humidity 25.5 per cent higher, and the wind velocity 3.2 miles an hour lower. There was also the normal light and darkness of day and night. These differences in climatic factors were sufficient to reduce the average hourly night transpiration to one-thirteenth of the day transpiration. At the same time, the evaporation from a free water surface was reduced only to one-eighth of the day evaporation.

TABLE 26.—*Average relative day and night transpiration and evaporation rates during nine consecutive days in 1910 and 30 days in 1914. (Taken from Tables 23 and 24.)*

Day or night	Transpiration	Evaporation	Mean temperature	Mean relative humidity	Mean wind velocity
	Per cent[1] (1)	*Per cent*[1] (2)	*Degrees F.* (3)	*Per cent* (4)	*Miles per hour* (5)
YEAR 1910					
Day 7 a.m.-7 p.m.	100	100	79.2	48.9	6.2
Night 7 p.m.-7 a.m.	8	10	63.8	78.1	1.8
Difference	....	....	15.4	29.2	4.4
YEAR 1914					
Day 7 a.m.-8 p.m.	100	100	85.6	59.8	8.1
Night 8 p.m.-7 am.	7	15	72.8	81.5	6.2
Difference	....	....	12.8	21.7	1.9
AVERAGE FOR TWO YEARS					
Day 7 a.m-7:30 p.m.	100	100	82.4	54.3	7.2
Night 7:30 p. m.-7 a. m.	7.5	12.5	68.3	79.8	4.0
Difference	....	....	14.1	25.5	3.2

[1] The average hourly transpiration and evaporation for the night (12 hours in 1910 and 11 hours in 1914) is expressed in per cent of the hourly day loss. For the exact losses in grams, see Tables 23 and 24.

Just why the transpiration rate should be reduced relatively so much more during the night than the evaporation rate is not fully understood. It would appear that there may be two chief possible causes, namely: (1) The internal heat developed by photosynthesis in the light is absent in the dark of the night. This factor may, however, be quite offset by the greater cooling effect of a more rapid transpiration in the daytime. (2) A comparative study of the condition of the stomatal apertures during the daylight and at night has shown that they are closed at night, and open in the day. At night the walls of the guard cells which form the stomatal aperture lie in such close contact that they merely appear as a heavy black line. On the other hand, in the daytime a very distinct, colorless aperture is found to exist between these cell walls. Occasional stomata show a slight aperture even at night.

As a result of these observations it is evident that the area exposed for diffusion is greatly reduced at night in the case of the corn leaf, while it is constant with a free water surface. Thus in case of the free water surface, the reduced night evaporation is caused solely by the reduced atmospheric demand, while with the plant it is primarily a combination of this cause with a greatly reduced total area of stomatal aperture.

DAILY TRANSPIRATION AND EVAPORATION IN RELATION TO CLIMATIC FACTORS.

During two years, 1910 and 1914, daily records were obtained, for a period of about one month each year, of the transpiration by corn plants, evaporation from free water surface, temperature, relative humidity, wind velocity, and sunshine. The climatic records, except percentage of sunshine, were obtained in the cornfield by means of self-recording instruments, as previously described and illustrated. (Fig. 4, page 47.)

The evaporation from a free water surface has been obtained each year by averaging together the losses from six evaporation jars of 36 square inch area standing at different elevations near the corn plants at intervals of 2 feet from the ground up. (See Fig. 3, page 46.)

The plants used for these measurements were grown in the experiments for testing the effect of different degrees of soil-moisture content on the water requirements of corn. For correlation with the climatic factors, only those groups of plants were averaged each year in which the shortage of water was not so great as to reduce the growth very abnormally.

In 1910 the daily losses were averaged for plants in the 60, 80, and 100 per cent soil saturation potometers. In 1914 the data for plants in 50, 70, and 95 per cent saturation were averaged. A complete record of the growth and water requirements of these plants may be found in Tables 53 and 55, pages 133 and 135.

Tables 27 and 28 and Charts X and XI contain a daily record for 1910 and 1914 of the average transpiration, evaporation, and climatic factors. The results appear to indicate clearly that transpiration from corn plants, and evaporation from a free water surface are similar phenomena and respond in a fairly similar degree to changes in the climatic factors. Transpiration is essentially evaporation. In the main, the daily losses for these two factors correlate and are fairly parallel. The occasional inconsistencies between the two may be largely due to the difference in the physical condition of the evaporating bodies and to difference in exposure.

In these tests the transpiration rate kept pace with free water evaporation when the atmospheric demands for moisture were high. When these evaporation demands were low, there was no definite tendency for the transpiration rate to be relatively less

TABLE 27.—*Relationship between the daily transpiration, evaporation, and climatic factors.*[1] *1910.*

24 hours ending 7 p. m. (1)	Water transpired per plant. (Av. 12 plants) *Grams* (2)	Water evap. from free water surface. (Av. 6 jars) *Grams* (3)	Mean hourly temperature. (7 a. m.-7 p. m.) *Degrees F.* (4)	Mean relative humidity. (7 a. m.-7 p. m.) *Per cent* (5)	Average hourly wind velocity 10 ft. above ground. (7 a. m.-7 p. m.) *Miles* (6)	Per cent of possible sunshine *Per cent* (7)
July 20	951	200	79.2	52.4	4.7	46
" 21	2,522	327	88.0	44.1	8.0	90
" 22	2,350	278	84.4	53.6	6.7	75
" 23	1,933	215	80.3	56.5	5.8	89
" 24	3,211	311	90.9	24.7	4.4	100
" 25	3,307	379	92.6	44.6	8.3	73
" 26	2,955	382	89.9	53.7	8.2	98
" 27	4,550	454	97.2	26.7	9.0	95
" 28	2,333	372	84.4	58.8	11.1	62
" 29	1,579	173	81.7	54.5	4.7	34
" 30	2,802	232	83.8	34.2	4.5	98
" 31	3,561	314	85.7	38.2	6.0	99
Aug. 1	3,982	374	90.3	46.4	6.8	91
" 2	3,419	311	88.2	53.1	4.6	85
" 3	2,143	204	82.6	45.7	6.7	88
" 4	2,479	236	77.2	45.7	5.6	84
" 5	1,867	163	76.7	43.3	4.7	48
" 6	1,582	147	74.2	43.0	4.4	30
" 7	2,533	193	79.0	42.1	3.7	84
" 8	857	91	71.1	73.2	5.5	24
" 9	2,438	319	76.1	40.6	9.0	100
" 10	2,815	256	80.4	41.3	6.5	89
" 11	2,571	259	81.5	57.2	6.9	93
" 12	2,518	241	83.0	58.6	8.1	65
" 13	708	105	75.1	77.3	5.7	13
" 14	1,098	139	78.6	68.3	6.0	45
" 15	2,094	163	82.4	61.3	4.8	65
" 16	2,850	219	88.3	56.2	4.7	72
" 18-19	1,104	108	75.2	68.7	5.0	61
" 20	2,165	198	82.0	63.1	3.7	99

[1] From Kiesselbach and Montgomery (1911).

reduced than the evaporation. This is contrary to a common belief that the plant exercises control over the water exit in relation to the climatic conditions.

Occasional days occur when all climatic conditions combine in extreme degree to make the atmospheric demand for moisture excessive. Examples of such days of maximum climatic combination and water loss were July 27 and August 1, 1910, and

July 21 and August 8, 1914. On the other hand, August 8, 1910, and July 18 and August 11, 1914, were examples of minimum water loss and low climatic values.

TABLE 28.—*Relationship between the daily transpiration, evaporation, and climatic factors. 1914.*

24 hours ending 7 p. m.	Water transpired per plant. (Av. 24 plants)	Water evap. from free water surface. (Av. 6 jars)	Mean hourly temperature. (7 a. m.-7 p. m.)	Mean relative humidity. (7 a. m.-7 p. m.)	Average hourly wind velocity 10 ft. above ground. (7 a. m.-7 p. m.)	Per cent of possible sunshine
	Grams	*Grams*	*Degrees F.*	*Per cent*	*Miles*	*Per cent*
(1)	(2)	(3)	(4)	(5)	(6)	(7)
July 16	3,001	315	86.7	62.8	17.0	74
“ 17	3,756	310	85.0	41.0	9.8	97
“ 18	670	64	70.0	82.2	5.7	5
“ 19	2,562	158	80.0	60.4	7.2	76
“ 20	1,917	154	79.0	69.4	9.8	14
“ 21	3,933	246	90.8	54.7	12.2	96
“ 22	2,957	236	89.2	63.8	8.7	61
“ 23	3,285	191	89.6	62.3	5.3	96
“ 24	2,510	141	86.9	66.3	5.9	59
“ 26	3,023	158	90.0	55.7	6.6	100
“ 27	3,500	235	92.2	60.9	5.9	74
“ 28	2,233	130	88.5	68.2	8.0	48
“ 29	1,642	191	79.7	72.2	10.6	14
“ 30	2,669	221	83.1	64.6	11.2	44
“ 31	1,643	161	78.1	65.8	9.3	97
Aug. 1	1,715	116	79.5	65.8	4.5	61
“ 2	2,137	173	82.4	66.0	6.9	40
“ 3	2,650	210	85.6	54.6	5.8	99
“ 4	2,746	198	85.2	53.1	8.4	89
“ 5	2,780	185	87.1	61.7	12.5	100
“ 6	2,647	190	86.3	60.7	3.6	86
“ 7	3,579	273	91.7	44.9	6.2	87
“ 8	3,911	308	91.1	49.5	8.6	86
“ 9	2,897	268	85.8	65.9	8.5	66
“ 10	2,026	181	78.2	45.5	4.2	96
“ 11	879	100	72.0	67.5	3.2	15
“ 12	2,577	218	84.6	50.5	8.6	91
“ 13	1,528	162	80.6	67.8	8.7	81
“ 14	2,075	165	79.3	59.5	7.8	73
“ 15	2,476	257	86.5	58.9	11.0	97

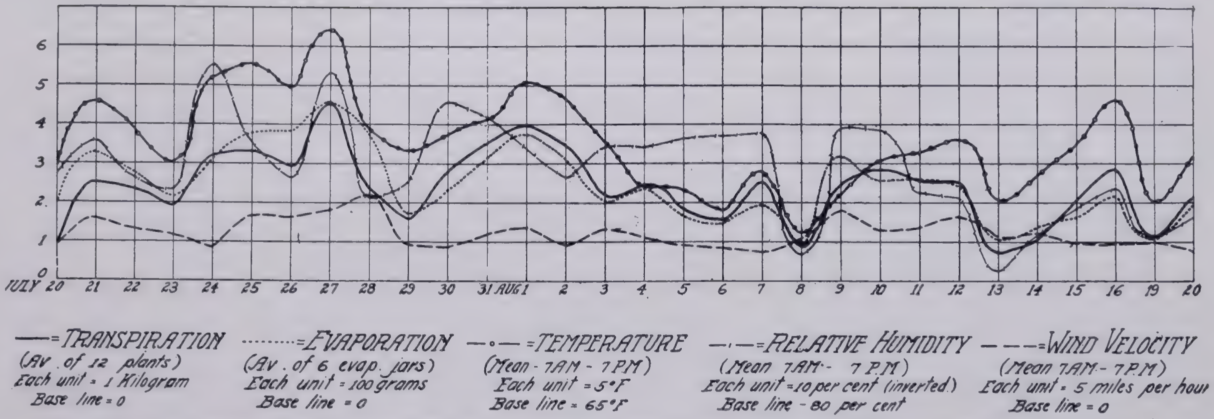


Chart X.—Daily variation in transpiration, evaporation, and climatic factors. 1910. (Graph of Table 27.)

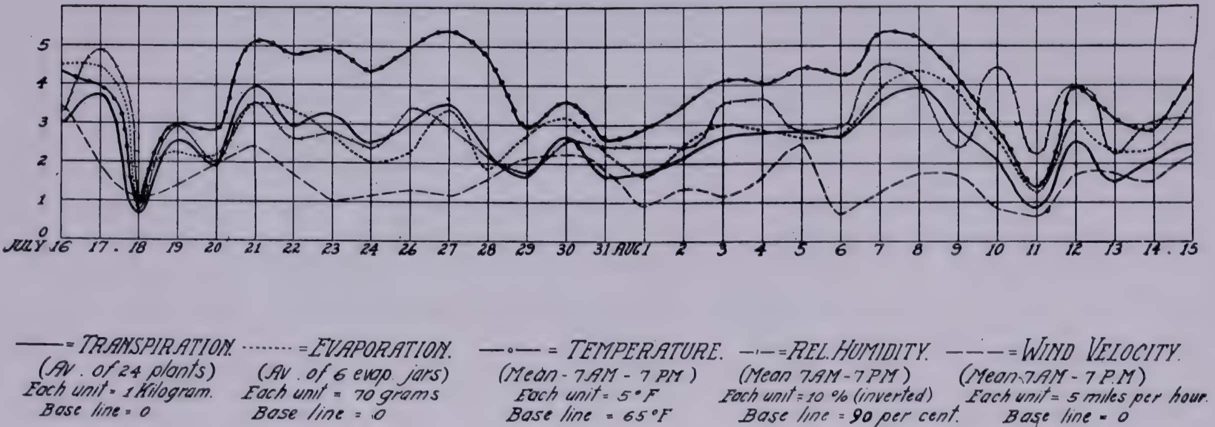


Chart XI.—Daily variation in transpiration, evaporation, and climatic factors. 1914. (Graph of Table 28.)

VARIATION IN THE DAILY TRANSPIRATION RATE AS INFLUENCED BY THE SOIL-MOISTURE CONTENT.

During two years, 1913 and 1914, eight plants of Hogue's Yellow Dent corn were grown in each of several different degrees of soil moisture. Summary data of the results secured relative to the growth and water requirements are included in Tables 56, 57, and 58, pages 137, 138, and 139. The average daily loss during about one month for the plants in each degree of soil moisture is recorded in Tables 29 and 30 and Charts XII and XIV. The plants were full grown and the leaf-area was practically constant during this period.

The relative daily transpiration in the different degrees of soil moisture is also shown in these tables by regarding the loss under the optimum moisture conditions (70 per cent saturation) as 100 per cent. The object is to show to what extent the fluctuations in the daily transpiration rates are independent of the soil-moisture content, under the conditions of these tests. These data are shown graphically in Charts XIII and XV. With a few exceptional days, the rates of water loss from plants in different degrees of soil moisture, altho markedly different in amount because of smaller plant development, are seen to be rather parallel in their daily fluctuation. There is no consistent or striking tendency for the plants lacking moisture to transpire a relatively large amount on days of low climatic values or relatively small amounts when climatic values are high, as measured in per cent of the loss from plants with ample soil moisture.

These facts, together with the failure of transpiration to lag behind free water surface evaporation in the heat of the day as shown in Charts VIII and IX, are contrary to the observations termed incipient drying by Livingston, B. E., and Brown, W. H., 1912. It seems entirely probable that had the water supply been sufficiently low to cause prolonged wilting, the transpiration would have been relatively low during the wilted condition. Wilting is accompanied by a reduced turgidity or a relatively low moisture content in the leaf. It is a principle in physics that water evaporates less readily from an object with a low moisture content than from one containing much moisture. Microscopic examination has shown that with a collapse of leaf tissue which accompanies wilting, the stomata are in a fairly closed condition, thus reducing the opportunity for diffusion.

TABLE 29.—*Relative daily transpiration from plants in different degrees of soil saturation. 1913.*

	Water transpired per plant			Per cent water transpired. Based on plants in 70 per cent relative saturation		
24 hours ending 7 p. m.	50 per cent relative saturation. (Av. 7 plants)	70 per cent relative saturation. (Av. 8 plants)	95 per cent relative saturation. (Av. 8 plants)	70 per cent relative saturation. (Av. 8 plants)	50 per cent relative saturation (Av. 8 plants)	95 per cent relative saturation.[1] (Av. 8 plants)
	Grams	*Grams*	*Grams*	*Per cent*	*Per cent*	*Per cent*
(1)	(2)	(3)	(4)	(5)	(6)	(7)
July 23	880	1,516	1,943	100	58.1	128.2
“ 24	1,200	1,807	2,465	100	66.4	136.4
“ 25	1,394	2,438	2,742	100	57.2	112.5
“ 27	667	2,107	2,402	100	31.7	114.0
“ 28	1,930	3,437	4,117	100	56.2	128.5
“ 29	1,911	3,700	4,186	100	51.6	105.0
“ 30	1,403	3,246	3,668	100	43.2	113.0
“ 31	1,716	3,219	3,655	100	53.3	113.5
Aug. 1	1,539	2,992	2,760	100	51.4	92.2
“ 2	1,970	3,759	3,927	100	52.4	104.5
“ 3	1,748	3,659	3,650	100	47.8	99.7
“ 5	2,202	4,141	4,190	100	53.2	101.2
“ 6	1,326	2,724	2,679	100	48.7	98.3
“ 7	2,043	4,046	4,172	100	50.5	103.1
“ 8	1,762	4,013	3,959	100	43.9	98.7
“ 9	2,270	4,526	4,540	100	50.2	100.3
“ 10	1,062	2,057	1,975	100	51.6	96.0
“ 11	776	1,394	1,208	100	55.7	86.7
“ 12	1,444	2,238	2,048	100	64.5	91.5
“ 13	2,465	4,495	4,372	100	54.8	97.3
“ 14	2,452	4,313	4,268	100	56.9	99.0
“ 15	2,551	4,508	4,327	100	56.6	96.0
“ 16	1,866	3,255	2,897	100	57.3	89.0
“ 17	536	1,525	1,603	100	35.1	105.1
“ 18	2,193	3,178	2,642	100	69.0	83.1
“ 19	1,330	2,324	2,265	100	57.2	97.5
“ 20	1,898	3,310	2,806	100	57.3	84.8
“ 21	822	1,662	1,498	100	49.5	90.1
“ 22	1,280	2,093	2,025	100	61.2	96.8
“ 23	1,444	2,093	2,293	100	69.0	109.5
“ 24	1,344	2,438	2,162	100	55.1	88.7
“ 25	1,544	2,833	2,578	100	54.5	91.0
“ 26	1,979	3,310	3,065	100	59.8	92.6
“ 27	1,930	4,399	3,973	100	43.9	90.3
“ 28	1,167	2,157	2,116	100	54.1	98.1
“ 29	1,267	2,193	1,943	100	57.8	88.6
“ 30	1,898	2,910	2,424	100	65.2	83.3
“ 31	1,939	3,455	2,924	100	56.1	84.6
Sept. 1	1,743	3,151	2,624	100	55.3	83.3

[1] The gradual reduction in the relative transpiration from the plants in 95 per cent soil saturation may perhaps be due to a more rapid deterioration of the plants in such wet soil.

TABLE 30.—*Relative daily transpiration from plants in different degrees of soil saturation. 1914*

24 hours ending 7 p. m.	Water transpired per plant				Per cent water transpired. Based on plants in 70% sat.			
	50 per cent relative saturation. (Av. 8 plants)	70 per cent relative saturation. (Av. 8 plants)	95 per cent relative saturation. (Av. 8 plants)	⅔ of 70 per cent relative saturation. (Av. 8 plants)	70 per cent relative saturation. (Av. 8 plants)	50 per cent relative saturation. (Av. 8 plants)	95 per cent relative saturation. (Av. 8 plants)	⅔ of 70 per cent relative saturation. (Av. 8 plants)
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Per cent* (6)	*Per cent* (7)	*Per cent* (8)	*Per cent* (9)
July 16...	2,465	3,464	3,074	2,320	100	71.1	88.7	67.0
“ 17...	3,332	4,445	3,491	2,592	100	74.9	78.5	58.3
“ 18...	545	794	672	672	100	66.1	84.6	84.6
“ 19...	2,275	2,987	2,424	2,061	100	76.1	81.1	69.0
“ 20...	1,657	2,116	1,979	1,480	100	78.3	93.5	69.9
“ 21...	3,487	4,599	3,714	2,533	100	75.8	80.7	55.1
“ 22...	2,520	3,500	2,851	2,161	100	72.0	81.1	61.7
“ 23...	2,933	3,868	3,055	2,806	100	75.8	78.9	72.5
“ 24...	2,265	2,801	2,465	1,866	100	80.8	88.0	66.6
“ 26...	2,692	3,369	3,010	2,029	100	79.9	89.3	60.2
“ 27...	3,142	4,004	3,355	2,660	100	78.4	83.7	66.5
“ 28...	1,993	2,583	2,125	1,557	100	77.1	82.2	60.3
“ 29...	1,312	1,993	1,621	1,294	100	65.7	81.3	64.9
“ 30...	2,624	3,087	2,297	2,057	100	85.0	74.4	66.6
“ 31...	1,544	1,911	1,475	1,439	100	80.7	77.1	75.3
Aug. 1...	1,607	2,107	1,430	1,321	100	76.2	67.8	62.7
“ 2...	1,970	2,488	1,952	1,725	100	79.1	78.4	69.3
“ 3...	2,574	3,019	2,356	1,984	100	85.2	78.0	65.7
“ 4...	2,651	3,046	2,542	2,057	100	87.0	83.4	67.5
“ 5...	2,615	3,369	2,356	1,870	100	77.6	69.9	55.5
“ 6...	2,433	2,946	2,561	1,984	100	82.5	86.5	67.3
“ 7...	3,487	4,159	3,092	2,107	100	83.8	74.3	50.7
“ 8...	3,700	4,377	3,655	2,220	100	82.2	83.5	50.7
“ 9...	2,729	3,469	2,492	2,025	100	78.6	71.2	58.4
“ 10...	2,179	2,170	1,730	1,671	100	100.4	79.7	77.0
“ 11...	903	1,007	726	549	100	89.6	72.1	54.6
“ 12...	2,592	2,828	2,311	1,843	100	91.6	81.7	65.2
“ 13...	1,380	1,929	1,276	1,221	100	71.5	66.1	63.3
“ 14...	2,043	2,147	2,034	1,498	100	95.1	94.6	69.8
“ 15...	2,606	2,605	2,216	1,639	100	100.0	85.0	62.9

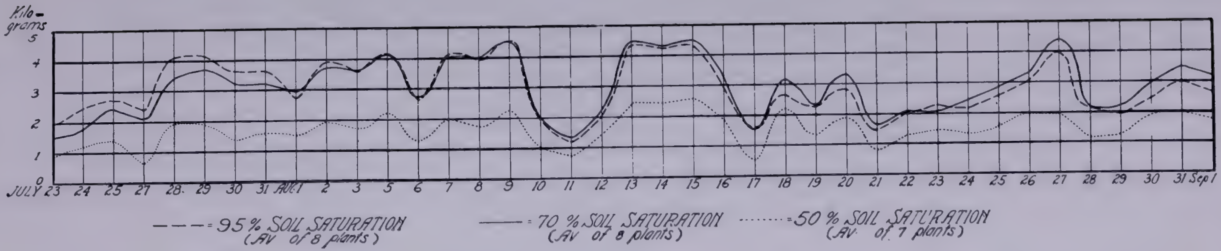


Chart XII.—Variation in the daily transpiration from corn plants in different degrees of soil moisture content. 1913. (Graph of Table 29.)

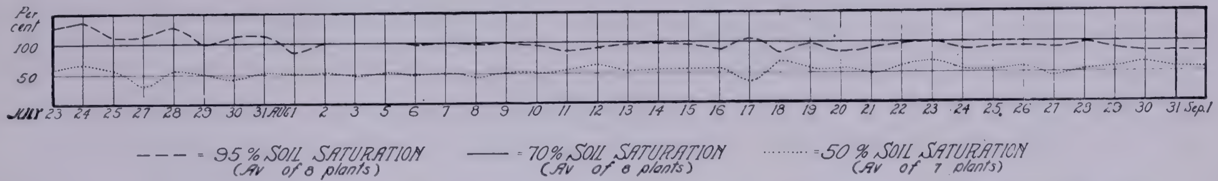


Chart XIII.—Graph of Chart XII with the transpiration rate from plants in soil 70 per cent saturated equalling 100 per cent, and the transpiration in the other saturations expressed in per cent of this, in order to bring out the degree of parallelism. 1913.

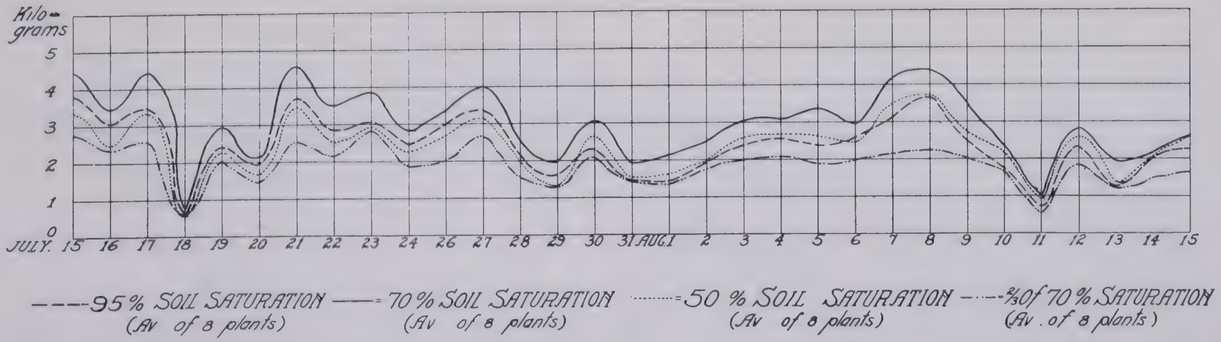


Chart XIV.—Variation in the daily transpiration from corn plants in different degrees of soil-moisture content. 1914. (Graph of Table 30.)

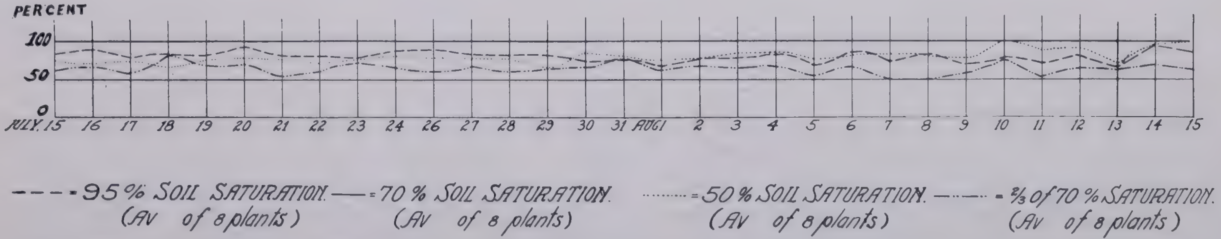


Chart XV.—Graph of Chart XIV with the transpiration rate from plants in soil 70 per cent saturated equalling 100 per cent, and the transpiration in the other saturations expressed in per cent of this, in order to bring out the degree of parallelism. 1914.

VARIATION IN WEEKLY TRANSPIRATION IN RELATION TO CLIMATIC FACTORS.

In 1914 a complete weekly record of transpiration and the climatic factors were obtained thruout the entire growing season. The results are given in Table 31 and Chart XVI.

The weekly water requirement gradually increases early in the season with the growth of the plant, regardless of the weather conditions. Late in the season the water requirement decreases, due to the ripening of the plant and consequent reduction in the amount of transpiring leaf surface. As the plant ripens, the leaves fail to function, become dry, and consequently have no moisture to be evaporated. In 1914, the leaf-area of the plants continued to increase until about July 8 and remained fairly constant until about August 15, when it gradually became reduced by the maturing of the plants. With a given variety, the dates of this cycle of development vary a few weeks in different years, according to climatic conditions. The season of 1914 was especially early.

TABLE 31.—*Weekly summary of transpiration from corn plants and weather factors thruout the growing season. (Average of 24 plants.) 1914.*

Week No.	Week ending 7 p. m.	Water transpired per plant. (Av. 24 plants)	Mean hourly temperature. (7 a. m.-7 p. m.)	Mean relative humidity (7 a. m.-7 p. m.)	Av. hourly wind velocity 10 ft. above ground. (7 a. m.-7 p. m.)	Per cent of possible sunshine
		Kilograms	*Degrees F.*	*Per cent*	*Miles*	*Per cent*
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	June 1	.141	77.6	74.6	8.5	67.3
2	“ 7	.412	79.6	77.2	13.8	67.1
3	“ 14	1.498	76.6	82.4	7.4	52.6
4	“ 21	6.430	78.0	75.3	7.5	61.3
5	“ 28	8.421	80.9	64.1	10.7	84.3
6	July 5	10.784	77.3	65.4	7.6	70.3
7	“ 12	20.667	85.7	62.2	8.6	85.0
8	“ 19	20.444	83.1	62.3	8.8	74.4
9	“ 26	20.202	86.2	64.5	7.7	70.4
10	Aug. 2	15.538	82.3	67.9	7.9	54.0
11	“ 9	21.214	86.1	57.7	7.6	87.6
12	“ 16	14.777	80.0	59.7	8.9	79.0
13	“ 23	14.381	85.0	66.0	7.6	66.6
14	“ 30	5.882	73.2	67.1	6.2	51.5
15	Sept. 6	7.030	79.0	55.1	7.1	78.0

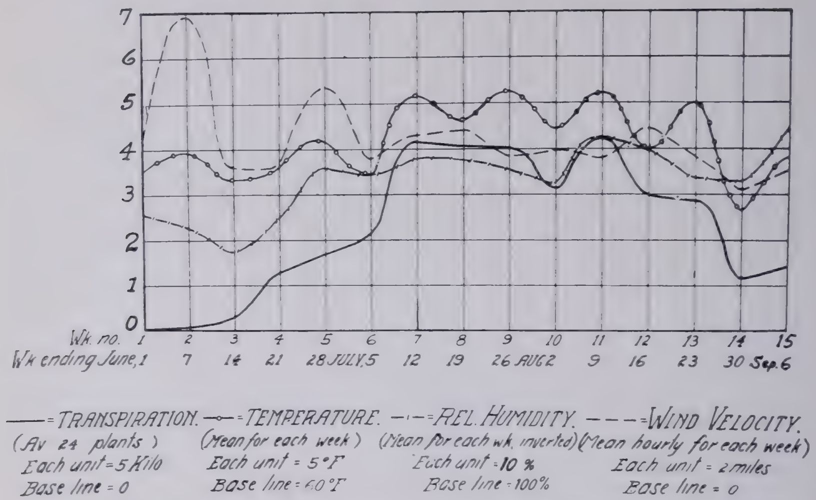


Chart XVI.—Weekly variation in transpiration and climatic factors thruout the corn growing season. 1914. (Graph of Table 31.)

TABLE 32.—*Weekly summary of water transpired thruout the growing season by corn plants growing in four different degrees of soil saturation. 1914.*

Week No.	Week ending 7 p. m.	Water transpired per plant (kilograms)			
		50 per cent relative saturation. (Av. 8 plants)	70 per cent relative saturation. (Av. 8 plants)	95 per cent relative saturation. (Av. 8 plants)	Two-thirds of 70 per cent relative saturation. (Av. 8 plants)
(1)	(2)	(3)	(4)	(5)	(6)
1	June 1.....	.138	.150	.136	.132
2	" 7.....	.386	.454	.395	.345
3	" 14.....	1.476	1.566	1.453	1.407
4	" 21.....	6.447	6.542	6.302	5.770
5	" 28.....	8.276	8.762	8.226	7.446
6	July 5.....	9.080	11.536	11.736	10.551
7	" 12.....	15.309	24.566	22.128	19.100
8	" 19.....	17.352	23.867	20.112	16.053
9	" 26.....	17.393	23.458	19.754	14.274
10	Aug. 2.....	14.188	18.169	14.256	12.049
11	" 9.....	20.189	24.384	19.068	14.242
12	" 16.....	15.214	16.408	12.908	10.419
13	" 23.....	15.036	15.795	12.312	9.838
14	" 30.....	6.701	6.406	4.540	3.909
15	Sept. 6.....	8.562	6.855	5.861	3.973

In a normal year the period from July 10 to August 20 is the most critical in corn production under Nebraska conditions, which may be ascribed to the high transpiration rate due to the combined high evaporating power of the atmosphere and the maximum leaf development of the plant. This is aside from the occasional blasting of the pollen and consequent reduction in grain development. Table 32 and Chart XVII show the transpiration by the week thruout the season for each of four degrees of soil moisture as tested in 1914.

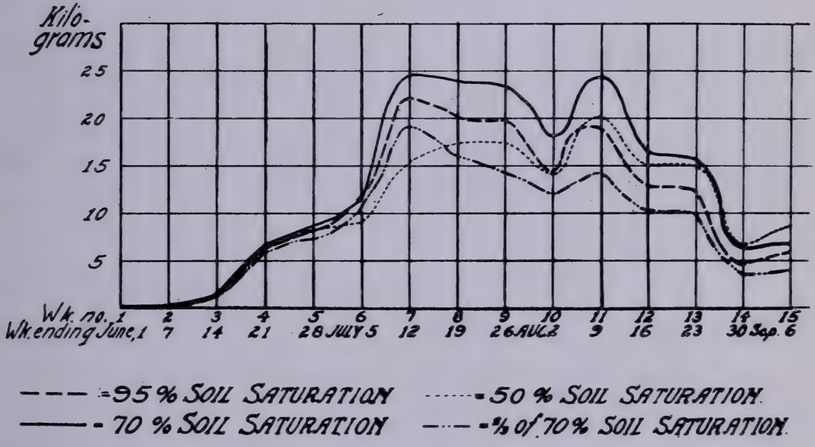


Chart XVII.—Weekly transpiration thruout the life of plants growing in different degrees of soil-moisture content. 1914. (Graph of Table 32.)

VARIATION IN YEARLY TRANSPIRATION.

As was seen in Table 31, the climatic conditions prevailing in July and August are the determining factors in the yield of corn, so far as transpiration is concerned. In 1914, 86 per cent of the entire transpiration from corn occurred during July and August. Accordingly, in an attempt to correlate the seasonal transpiration with evaporation and the climatic factors, during the five consecutive years 1910-1914, the data for the two months of July and August were used.

Plants taken for this comparison were grown in standard potometers in the cornfield under similar conditions as to corn variety, soil fertility, soil moisture, soil mass, and the exclusion of sources of error as surface evaporation and the entrance of rain. The yearly differences recorded in Table 33 may therefore in the main be ascribed to variations in the climatic conditions affecting the evaporating power of the air.

For these yearly comparisons the evaporation from a free water surface is based on the loss from the evaporation jar 10 feet above the ground. This jar stood higher than the surrounding corn each year, and consequently always had identical exposure.

Since there was some likelihood that our weather instruments might vary a degree in adjustment between the different years, it was thought best to eliminate such a possibility of error, and consequently the seasonal weather records were calculated from hourly records taken by the United States Weather Bureau three miles distant.[1] In a few instances when its data were incomplete they were supplied from our own records. These weather data are compiled in Table 34.

The summary tables indicate that there is a marked difference in the evaporating power of the atmosphere in different seasons, which may be accounted for by seasonal climatic variations. There is a rather consistent relationship in the relative seasonal variations between the (1) transpiration per unit dry matter, (2) transpiration per unit leaf-area, and (3) evaporation from a free water surface.

The two years 1913 and 1914 offer an extreme contrast in the water requirements. The data for these two years have been compiled in Table 35 for comparison with similar data obtained during two years 1911-1912 under controlled greenhouse conditions, in which the effect of a difference in relative humidity was the object sought.

The comparison shows a very similar difference in the prevailing temperature and humidity under natural field conditions in 1913 and 1914, as existed in the greenhouse experiments of 1911 and 1912 in which a difference of 22 per cent in relative humidity was artificially maintained. The complete data for these greenhouse experiments follow.

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[1] The author is indebted to Professor G. A. Loveland, section director of the United States Weather Bureau, for access to the original hourly records from which these seasonal climatic data were compiled.

TABLE 33.—*Seasonal variation in water requirement of corn as related to climatic conditions in different years expressed in free-water-surface evaporation.*

Year	No. of potometers averaged[1]	Dry matter		Total leaf-area per plant	Total water transpired	Transpiration per			Evaporation from free-water surface of 36 sq. in. area		
		Ear	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area	July	August	Average
		Grams	*Grams*	*Sq. in.*	*Kilogr's*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1914	4	242	443	1,193	123	507	277	103	270	298	284
1913	80	173	372	1,071	165	976	445	155	511	442	476
1912	48	234	407	805	106	456	261	134	393	310	351
1911	4	210	413	890	141	672	341	158	468	314	391
1910	4	237	484	1,313	127	537	262	97	325	242	283

[1] Although only 4 potometers were averaged some years, many other potometers, though not quite comparable, gave similar results.

TABLE 34.—*Mean weather factors (7 a. m. to 7 p. m.) during July and August for five years, 1910-1914.*

Year	Mean temperature			Mean relative humidity			Mean hourly wind velocity			Mean per cent possible sunshine		
	July	Aug.	Av.	July	Aug.	Av.	July	Aug.	Av.	July	Aug.	Av.
	Degrees F	*Degrees F*	*Degrees F*	*Per cent*	*Per cent*	*Per cent*	*Miles*	*Miles*	*Miles*	*Per cent*	*Per cent*	*Per cent*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1914	88.2	80.6	84.4	57.8	60.3	59.0	8.4	9.8	9.1	73.0	70.0	71.5
1913	85.6	88.2	86.9	42.7	38.9	40.8	12.1	9.5	10.8	83.0	80.0	81.5
1912	88.1	79.6	83.9	46.5	55.7	51.1	11.9	10.3	11.1	79.0	74.0	76.5
1911	83.6	79.4	81.5	44.8	56.4	50.6	12.2	9.5	10.8	82.0	80.0	81.0
1910	82.9	77.5	80.2	50.7	55.1	52.9	9.1	9.6	9.3	77.0	65.0	71.0

TABLE 35.—*Effect of seasonal climatic differences upon water requirements of corn exposed under natural conditions as compared with effect of controlled climatic differences under greenhouse conditions.*

FIELD

	1913	1914	Difference	Ratio 1913 to 1914
Mean temperature, 12 hours of the day (degrees F.)	86.9	84.4	2.5	....
Mean relative humidity, 12 hours of the day (per cent)	40.8	59.0	18.2	....
Mean wind velocity, 12 hours of the day (miles per hour)	10.8	9.1	1.7	....
Mean per cent sunshine (per cent)	81.0	71.9	9.1	....
Water transpired per gram dry weight (grams)	445.0	277.0	....	100:62
Water transpired per square inch leaf-area	155.0	103.0	....	100:66
Water evaporated from 36 square inch free water surface (grams)	476.0	284.0	....	100:60

GREENHOUSE

	Average for 1911 and 1912			
	Dry greenhouse	Humid greenhouse	Difference	Ratio dry to humid
Mean temperature, 12 hours of the day (degrees F.)	91.0	89.3	1.7	....
Mean relative humidity, 12 hours of the day (per cent)	45.0	67.0	22.0	....
Water transpired per gram dry weight (grams)	343.6	200.2	....	100:58
Water transpired per square inch leaf-area (grams)[1]	38.95	24.15	....	100:62
Water evaporated from 36 square inch free water surface (grams)	128.33	68.97	....	100:54

[1] Water used per square inch leaf-area in the greenhouse is low, because the plants were only grown to the silking stage. For complete data and notes on greenhouse tests see pages 111 to 114.

RELATION OF TRANSPIRATION TO ATMOSPHERIC HUMIDITY.

To secure further data relative to the effect of atmospheric humidity on transpiration, the previously-published greenhouse work of 1911 was continued and extended in 1912. Humidity is the easiest of all the climatic factors to control in greenhouses independently of other factors.

Two greenhouses were employed. One was maintained at the normal humidity by eliminating all possible sources of dampness. The atmosphere in the other was maintained as humid as possible by means of fine atomizers attached to the water system, and by keeping the floor and benches wet. The ventilators were so adjusted that only very slight differences in temperature resulted. A self-recording thermometer and hygrometer were kept in each greenhouse. Since transpiration at night has been found to be only 7 or 8 per cent as great as in the daytime, the weather factors for the day only should be used in studying their effect upon the total transpiration. The results of three tests in 1911 and 1912 are contained in Tables 36, 37, and 38 and are summarized in Table 39.

In 1911 all of the plants were grown in the subirrigation type of potometers, 16 by 36 inches, filled with a fertile loam. Two plants grew in each potometer. In 1912 part of the plants were grown singly in the same style of potometer as was used in 1912 and part were grown singly in the small 4-gallon potometers containing 18 kilograms of a fertile compost-loam mixture. A small variety of pop corn was grown in these small potometers so that the plants might grow for a relatively long time before the small amount of soil should become a seriously limiting factor. All plants were harvested at the same time, at about the silking stage.

Table 39 shows that largely as the result of 22 per cent higher humidity and 1.75° F. lower temperature during the day, only 58 per cent as much water was transpired per unit of dry matter. and 62 per cent as much per unit leaf-area, while the evaporation from a given free water surface was 54 per cent as much in the humid as in the dry greenhouse.

EFFECT OF PREVIOUS CONDITION OF GROWTH ON TRANSPIRATION.

Pop corn plants were used in this experiment which had been grown almost to the silking stage in either the dry or the humid greenhouse in 1912 under the climatic conditions described in Table 38. At the end of the eighth week, part of the plants were transferred from each greenhouse to the opposite greenhouse and there compared in relative transpiration rate with the

TABLE 36.—*Relation of water used by plants to atmospheric humidity. 1911. Hogue's Yellow Dent corn used. Grown in potometers 16 by 36 inches. Harvested at silking stage.*

	Dry greenhouse	Humid greenhouse	Ratio dry to humid
Number of potometers averaged	5	5	....
Mean temperature, 12 hours of night (degrees F.)	80.0	75.0	....
Mean temperature, 12 hours of day (degrees F.)	91.0	88.0	....
Mean relative humidity, 12 hours night (per cent)	48.0	72.0	....
Mean relative humidity, 12 hours day (per cent)	37.0	58.0	....
Average dry weight per plant	83.8	107.7	....
Average leaf-area per plant (square inches)	1,079.0	1,070.0	....
Total water used per plant (kilograms)	28.473	23.030	....
Water used per gram dry weight (grams)	340.0	191.0	100:56
Water used per square inch leaf-area (grams)	27.3	19.2	100:70
Water evaporated from 36 square inches free water surface (grams)	3,891.0	2,187.0	100:56

TABLE 37.—*Relation of water used by plants to atmospheric humidity. 1912. Hogue's Yellow Dent corn used. Grown in potometers 16 by 36 inches. Harvested at silking stage.*

	Dry greenhouse	Humid greenhouse	Ratio dry to humid
Number of potometers averaged	5	5	....
Mean temperature 12 hours of day (F.)	91.0	90.0	....
Mean temperature 12 hours of night (F.)	81.0	76.0	....
Mean rel. humidity 12 h'rs of day (per cent)	49.0	72.0	....
Mean rel. humidity 12 h'rs of night (per cent)	67.0	82.0	....
Average dry weight per plant (grams)	100.9	90.5	....
Average leaf-area per plant (square inches)	750.0	729.0	....
Total water used per plant (kilograms)	33.640	19.067	....
Grams water used per gram dry weight (grams)	333.4	210.7	100:63
Grams water used per square inch leaf-area (grams)	44.85	26.14	100:58
Water evaporated per square inch free water surface (grams)	151.39	80.03	100:53

TABLE 38.—*Relation of water used by plants to atmospheric humidity. 1912. Pop corn used. Grown in 4-gallon potometers. Harvested at silking stage.*

	Dry green-house	Humid green-house	Ratio dry to humid
Number of potometers averaged	10	9	....
Mean temperature 12 hours of day (F.)	91.0	90.0	....
Mean temperature 12 hours of night (F.)	81.0	76.0	....
Mean rel. humidity 12 h'rs of day (per cent)	49.0	71.0	....
Mean rel. humidity 12 h'rs of night (per cent)	67.0	82.0	....
Average dry weight per plant (grams)	67.9	71.9	....
Average leaf-area per plant (square inches)	543.0	528.0	....
Total water used per plant (kilograms)	24.279	14.304	....
Grams water used per gram dry weight (grams)	357.30	198.80	100:56
Grams water used per square inch leaf-area (grams)	44.70	27.11	100:61
Water evaporated per square inch free water surface (grams)	125.50	66.20	100:53

TABLE 39.—*Relation of water used by corn plants to atmospheric humidity. Average of three tests in 1911 and 1912.*

	Dry green-house	Humid green-house	Ratio dry to humid
Number of potometers averaged	20	19	....
Mean temperature 12 hours of day (F.)	91.0	89.3	....
Mean temperature 12 hours of night (F.)	80.7	75.7	....
Mean rel. humidity 12 h'rs of day (per cent)	45.0	67.0	....
Mean rel. humidity 12 h'rs of night (per cent)	60.7	78.7	....
Average dry weight per plant (grams)	84.2	90.0	....
Average leaf-area per plant (square inches)	790.7	775.7	....
Total water used per plant (kilograms)	28.797	18.803	....
Water used per gram dry weight (grams)	343.6	200.2	100:58
Water used per square inch leaf-area (grams)	38.95	24.15	100:62
Water evaporated from 1 sq. in. free water surface (grams)	128.33	68.99	100:54

[1] Compiled from Tables 36, 37, and 38.

For a discussion of method used in compiling averages for two or more years see page 42.

plants which had constantly been grown under those conditions. This relative transpiration rate was based on leaf-area. Leaf measurements were taken at the beginning and again at the end

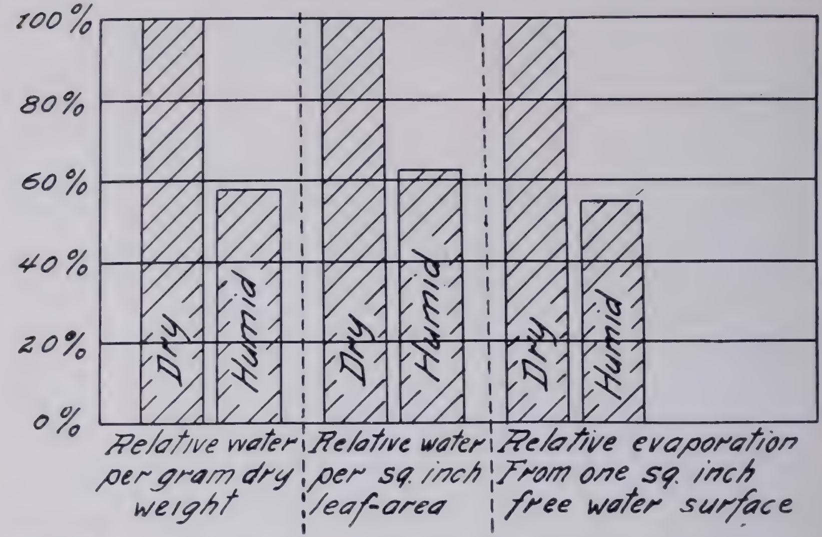

Chart XVIII.—Relative transpiration from corn plants and evaporation from free water surface in two greenhouses of high and low atmospheric humidity. Two-year average, 1911 and 1912. (Graph of Table 39.)

TABLE 40.—*Effect of previous condition of growth on transpiration. 1912. Pop corn used. Grown in 4-gallon potometers.*

	Average leaf-area	Transpiration week ending July 16	Transpiration week ending July 23	Transpiration from 1 sq. in. leaf-area	
				First week	Second week
	Sq. in.	*Grams*	*Grams*	*Grams*	*Grams*
Plants grown continuously in dry greenhouse. Average of 10 plants	543.0	4,561	4,904	8.40	9.03
Plants transferred from humid to dry greenhouse. Average of 8 plants	547.0	4,671	4,494	8.54	8.21
Plants grown continuously in humid greenhouse. Average of 10 plants	528.0	3,191	2,813	6.04	5.33
Plants transferred from dry to humid greenhouse. Average of 8 plants	508.0	3,043	2,668	5.99	5.25

of the two-week period following the transfer, and averaged for this purpose. The results are given in Table 40.

The results indicate that there was no significant adaptation of the plants under one condition of atmospheric humidity which would either retard or accelerate the transpiration when brought under markedly different conditions.

EFFECT OF TRANSPIRATION ON LEAF TEMPERATURE.

It is a well-known principle in physics that evaporation has a cooling effect upon the evaporating body. It, therefore, seems reasonable that the evaporation from the leaf should have a modifying influence upon the atmospheric temperature affecting it. The resultant reduction in leaf temperature must serve to reduce the transpiration rate. In this manner transpiration tends to reduce its own magnitude. Some preliminary data relative to leaf temperatures were secured during 1912 and 1913. In 1913 the comparative temperatures were determined for a transpiring leaf of a corn plant growing in the cornfield, and of a dry, dead leaf having the same exposure. Being fairly similar objects, the two leaves should have acquired rather similar temperatures had not the evaporation from the living leaf exerted a cooling effect. Water taken in by the roots naturally acquires the relatively low temperature of the soil, and its movement thru the stalk and leaves also exerts a somewhat cooling effect. The data follow in Table 41.

TABLE 41.—*Summary of plant temperatures showing the effect of transpiration upon leaf temperature. (Average for 7 days, August 25 to 30, 1913.)*

Time of day	Sun or shade	Average temperatures in sun and shade		
		Green leaf	Dry leaf	Air
		Degrees F.	*Degrees F.*	*Degrees F.*
(1)	(2)	(3)	(4)	(5)
8:00 a. m.	Sun	79.8	81.2	78.4
	Shade	76.4	77.6	75.8
	Average	78.1	79.4	77.1
2:00 p. m.	Sun	95.4	104.0	99.5
	Shade	93.8	98.0	97.0
	Average	94.6	101.0	98.2
5:30 p. m.	Sun	91.7	96.7	97.2
	Shade	90.2	94.0	94.2
	Average	90.9	95.3	95.7
Daily av. in sun		88.9	94.0	91.7
Daily av. in shade		86.8	89.9	89.0
Daily av.		87.8	91.9	90.3

The data indicate that a transpiring leaf is uniformly cooler than a dead one, amounting (under the high air temperatures of 1913) to a difference of 8.5° F. in the sun at 2 p. m. when transpiration is maximum, and 4.2 degrees in the shade at the same time. Averaging the sun and shade temperature for the day we find that the average daily temperature of the green leaf is 2.2° F. below the air temperature, while the dry leaf is 1.6° F. higher than the air. A probable reduction of 4° F. in the temperature of the leaf due largely to the transpiration is sufficient to exert a marked protection against water loss. The degree of leaf-temperature reduction would doubtless vary with climatic conditions.

We cannot conclude that it is one of the purposes of transpira-

TABLE 42.—*Summary of plant temperature records in the cornfield. 1912. All temperatures were taken in the shade. (Average for week, August 25 to August 31.)*

Time of day	Degrees temperature in shade				
	Leaf	Stalk	Leaf sheath	Ear	Air
(1)	*Degrees F.* (2)	*Degrees F.* (3)	*Degrees F.* (4)	*Degrees F.* (5)	*Degrees F.* (6)
7:30 a. m.	76.3	73.7	73.9	72.8	75.6
2:00 p. m.	90.7	87.4	86.0	87.8	93.3
5:30 p. m.	84.2	83.0	81.0	85.2	87.6
Average	83.7	81.4	80.3	81.9	85.5

TABLE 43.—*Summary showing the temperature of different parts of the growing corn plant. (Average for 7 days—August 4 to 9, 1913.)*

Time of day	Degrees temperature in shade				
	Leaf	Stalk	Leaf sheath	Ear	Air
(1)	*Degrees F.* (2)	*Degrees F.* (3)	*Degrees F.* (4)	*Degrees F.* (5)	*Degrees F.* (6)
7:30 a. m.	76.6	74.8	74.8	74.8	76.3
2:00 p. m.	93.1	90.6	90.6	92.3	95.8
5:30 p. m.	92.0	91.5	91.6	90.8	95.1
Average	87.2	85.6	85.7	86.0	89.1

tion to reduce water loss by reducing leaf temperature, but rather that it is simply a coincidence.

Additional temperatures recorded in Tables 42 and 43 were taken in 1912 and 1913 to determine the relative temperature of the leaf and other parts of the plant as compared with the air temperature. The temperature within the stalk, underneath the leaf sheath, and underneath the husks surrounding the ear were rather similar, while the leaf temperature was 2 to 3° F. higher and yet approximately 2° F. cooler than the air.

The leaf temperatures were all taken by inserting the thermometer momentarily in a fold of the leaf, taking care to eliminate the effect of body heat of the operator. Altho this method is not very refined, it is probable that these temperatures are approximately correct. An elaborate method for determining leaf temperatures has been used and described by Shreve (1914). An electric potentiometer method for determining leaf-temperature is described by Ehlers (1915). A study of leaf-temperatures at this station will be continued with the use of thermocouples properly connected with a potentiometer.

RELATIVE RATES OF EVAPORATION FROM EQUAL AREAS OF FREE WATER SURFACE AND LEAVES OF GROWING CORN PLANTS.

In 1914, 24 potometers, each containing one corn plant with a fully developed leaf-area, were weighed each day for a period of 30 days, and the daily transpiration determined. Likewise the evaporation from six evaporation jars of 36 square inch free water surface, standing at regular intervals ranging from the ground surface to 10 feet above the ground, was determined daily for the same interval of time. The total average transpiration for one corn plant of 1,378 square inch leaf-area during the 30 days was 75,924 grams, which is equal to 55.1 grams water per square inch.

The total average evaporation for one evaporation jar of 36 square inch area was 5,915 grams, which is equal to 164 grams per square inch. Accordingly, the transpiration rate per square inch leaf-area was 33.6 per cent of the evaporation from a square inch free water surface.

During 30 days in 1914, the hourly transpiration was determined for one corn plant having 1,500 square inches leaf-area. The evaporation from a free water surface standing midway between the top and base of the plant was also determined hourly. The average transpiration per day was 3,112 grams, which is equal to 2.1 grams per day per square inch leaf-area. The average evaporation per day was 227 grams, which is equal to 6.3 grams per square inch free water surface.

In this test the transpiration rate per square inch leaf-area was 33.3 per cent of the evaporation from a square inch free water surface.

In 1910, the daily transpiration was determined during 30 days for 12 corn plants after the leaf-area was fully developed. Likewise the evaporation from six evaporation jars of 36 square inch free water surface at elevations above the ground of 0, 2, 4, 6, 8, and 10 feet was determined. The total average transpiration for one corn plant of 1,209 square inches leaf-area during the 30 days was 71,277 grams, which is equal to 58.9 grams per square inch.

The total average evaporation for one evaporation jar of 36 square inches free water surface was 7,363 grams, which is equal to 205 grams per square inch area. According to these data, the transpiration rate per square inch leaf-area was 29 per cent as great as the evaporation from a square inch free water surface.

As an average for all three tests in 1910 and 1914 we find that the evaporation from a square inch of leaf area was 32 per cent as great as the evaporation from a square inch of free water surface. Since a corn leaf has two epidermal surfaces from which water evaporates, one may calculate that the evaporation from a given area of free water surface is approximately six times as great as from an equal area of leaf surface.

The above leaf and free water surface evaporation data are quite comparable for the reason that the leaf-area was fairly constant during the time of the tests.

At the Nebraska Agricultural Experiment Station an average acre of well-adapted corn has two acres of leaves, or 4 acres of leaf surface, counting both sides.

THE GROWING CROP AS A PROTECTION AGAINST WATER-DISSIPATING INFLUENCES.

EVAPORATION STUDIES IN CORN AND SMALL-GRAIN FIELDS.

For a number of years, botanists have been studying ecological conditions of natural habitats of native plants. Similar principles may be applied in the study of cultivated fields.

In fact, our study of crop production is largely one of applied plant physiology and ecology. Among the least investigated features of this field ecology are the water dissipating influences as expressed by the evaporation power of the air within the field itself. The extensive data concerning the relative evaporation and transpiration rates reported in pages 87 to 116 have shown that these two phenomena (which are really only one phenomenon acting on two somewhat different media) are strikingly parallel, and respond in a rather similar degree to similar influences. It is entirely probable that, soil conditions being equal, the relative evaporation rate in two conditions, localities, or regions is a very good index as to the relative water requirements of similar crops grown under those conditions.

Two of the chief objects sought in the tests which follow were: (1) In what degree is the vegetation in a field a protection against excessive transpiration as measured in terms of evaporation from a free water surface at different elevations within the growing crop; and (2) to what degree is such a crop likely to serve as a protection against moisture evaporation from the soil.

The method used was to place a number of evaporation jars of 36 square inch surface area and 1 gallon capacity at different elevations in corn and small-grain fields. The lowest jar was placed with its surface level with the ground (unless otherwise stated) and the highest jar stood above the crop even after it had attained its maximum growth. Studies were made in the cornfield in 1912, 1913, and 1914, in spring wheat in 1912, and in oats in 1913.

In the cornfield, the evaporation jars which regularly stood at different elevations at the north end of one of the potometer pits were not used for these determinations. But a separate series of jars was placed out in the cornfield under strictly normal field conditions where Hogue's Yellow Dent corn was grown three plants in a hill, with hills 3 feet 6 inches apart. Moving leaves and birds were prevented from disturbing the water by arching woven chicken wire over the jar. Normally, the water was $\frac{1}{2}$ inch below the surface of the jars, which were weighed in grams each evening and the evaporated water replaced to a standard weight.

The results are contained in Tables 44 to 50. It must be borne in mind that crops do not make exactly the same growth each year and are lodged more some years by wind than others. Such influences disturb somewhat the normal relationships from year to year.

The evaporation rate within the crop increases with an increase in elevation. The crop doubtless causes a higher atmospheric humidity and lower wind velocity at the bottom of the vegetation, which change with the elevation. It certainly would appear that a plant afforded the protection of fellow plants under field conditions, against the water-dissipating influences of the atmosphere, should transpire relatively less water than an isolated plant in an exposed place. This self-protection in mass makes it possible to grow a larger amount of vegetation on a given amount of soil moisture than would be possible if the plants were freely exposed.

In all tests the evaporation at the surface of the ground bore a rather constant proportion to the evaporation from the highest jar. These ratios were: Corn, 1912, 0.31; corn, 1913, 0.36; corn, 1914, 0.31; spring wheat, 1912, 0.36; oats, 1913, 0.39. From these figures it may be concluded that, as a general principle, the water-dissipating influences are approximately three times as effective just above the growing crop as at the ground. The relationship may be expected to vary with the stage of development and character of the crop. In an open, bare field, the evaporation rates would not be identical above the ground and at the surface, but rather increase with elevation. However, we can assume that the above reduction in evaporation rate represents in large measure the degree of protection afforded by the crop. This has an important effect on reducing the loss of

TABLE 44.—*Weekly summary of evaporation from free water surfaces 36 square inches in area at six elevations in a cornfield. 1912.*

Av. daily evaporat'n for week ending	Elevation of evaporating surface above ground						Average of six elevations
	6 in.	2 ft.	3.5 ft.	5 ft.	8 ft.	10 ft.	
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Grams* (6)	*Grams* (7)	*Grams* (8)
June 5..	203	354	366	401	450	452	371
" 12[1]..	....	....	....	....	....	....	....
" 19..	120	211	202	218	224	236	202
" 26..	179	302	308	333	343	359	304
July 3..	141	299	331	369	370	364	312
" 10..	203	378	436	543	529	519	435
" 17..	149	244	346	380	444	434	333
" 27..	86	126	164	226	377	337	219
Aug. 3..	85	130	153	165	313	332	196
" 10..	30	55	70	86	188	189	103
" 17..	55	113	139	163	321	344	189
" 24..	56	108	122	150	265	278	163
" 31..	98	173	190	223	413	440	256
Sept. 7..	95	185	192	241	451	453	270
" 14..	69	124	136	173	285	296	181
Daily av.	112	200	225	262	355	360	252

[1] Satisfactory data could not be obtained this week because of heavy rains.

TABLE 45.—*Weekly*[1] *summary of evaporation from free water surfaces 36 square inches in area, at five elevations in a cornfield. 1913.*

Av. daily evaporation for week ending 7 p. m.	Elevation of evaporating surface above ground					Average of five elevations
	0 ft.	3.5 ft.	6 ft.	8 ft.	10 ft.	
	Grams	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*
(1)	(2)	(3)	(4)	(5)	(6)	(7)
July 7.......	206	384	439	472	486	397
" 14.......	197	323	440	466	520	389
" 21.......	203	290	425	481	495	379
" 28.......	124	178	285	340	542	294
Aug 4.......	127	216	352	411	415	304
" 11.......	160	250	398	487	484	356
" 18.......	162	211	366	432	447	324
" 25.......	151	196	306	357	368	276
Sept 1.......	191	256	408	484	496	367
" 8.......	204	283	440	529	539	399
Average......	172.5	259	386	446	479	348.5

[1] The corn was planted May 25 and had made considerable growth when the test was started.

TABLE 46.—*Weekly*[1] *summary of evaporation from free water surfaces of 36 square inches in area, at five elevations in a cornfield. 1914.*

Av. daily evaporation for week ending 7 p. m.	Elevation of evaporation surface above ground					Average of five elevations
	0 in.	36 in.	68 in.	96 in.	120 in.	
	Grams	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*
(1)	(2)	(3)	(4)	(5)	(6)	(7)
June 28......	128	183	284	340	364	260
July 5......	105	113	183	213	224	168
" 12......	90	142	200	278	305	203
" 19......	103	132	177	270	280	192
" 26......	61	99	150	237	259	161
Aug 2......	61	99	139	223	238	152
" 8......	81	142	199	329	359	222
" 16......	84	114	175	303	329	201
" 23......	109	175	231	356	393	253
" 30......	79	104	134	196	191	141
Sept 6......	89	147	186	272	283	195
Average......	90	132	187	274	293	195.2

[1] The corn was planted May 26 and had made considerable growth when the test was started.

TABLE 47.—*Evaporation from free water surfaces 36 square inches in area at four elevations in a spring wheat field. 1912.*

Height of jar above ground	Average daily evaporation	Average daily per cent evaporation
Feet	*Grams*	*Per cent*
0	151	39
1½	277	71
3	341	87
4½	389	100

TABLE 48.—*Weekly*[1] *summary of evaporation from free water surfaces 36 square inches in area at four elevations in an oat field. 1913.*

Average daily evaporation for week ending 7 p. m.	Elevation of evaporating surface above ground				Average of four elevations
	0 in.	15 in.	30 in.	45 in.	
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Grams* (6)
OATS GROWING					
May 25	72	129	142	157	125
June 1	96	208	255	297	214
" 8	64	108	133	159	116
" 15	91	144	255	291	195
" 22	119	169	271	342	225
" 29	171	243	343	468	306
July 6	136	218	301	401	264
Average	107	174	243	302	206
OATS HARVESTED					
July 13	209	277	315	357	289
" 18	409	579	619	672	570
Average	309	428	467	515	430

[1] The oats were 4 inches high when the test started.

TABLE 49.—*Weekly summary of evaporation from free water surfaces 36 square inches in area at four elevations in an oat field. Evaporation expressed as percentage of evaporation from the upper jar. 1913.*

Average daily evaporation for week ending 7 p. m.	Elevation of evaporating surface			
	0 in.	15 in.	30 in.	45 in.
(1)	*Per cent* (2)	*Per cent* (3)	*Per cent* (4)	*Per cent* (5)
	OATS GROWING			
May 25	46	82	90	100
June 1	32	70	86	100
" 8	40	68	84	100
" 15	31	49	88	100
" 22	35	49	79	100
" 29	37	52	73	100
July 6	34	54	75	100
Average	36	61	82	100
	OATS HARVESTED			
July 13	59	78	88	100
" 18	61	86	92	100
Average	60	82	90	100

TABLE 50.—*Summary showing relative free water evaporation rates at different elevations in corn and small-grain fields. 1912-1914.*

Evap. jar No.	Elevation above the ground				
	1	2	3	4	5
(1)	*Inches* (2)	*Inches* (3)	*Inches* (4)	*Inches* (5)	*Inches* (6)
Corn, 1912	6	24	42	60	108[1]
Corn, 1913	0	42	72	96	120
Corn, 1914	0	36	68	96	120
Spring wheat, 1912	0	18	36	54	....
Oats, 1913	0	15	30	45	....
	PER CENT EVAPORATION BASED ON UPPER JAR				
Corn, 1912	31	55	63	73	100[1]
Corn, 1913	36	54	81	93	100
Corn, 1914	31	45	64	93	100
Spring wheat, 1912	39	71	87	100	....
Oats, 1913	36	61	82	100	....

[1] Average of two upper jars.

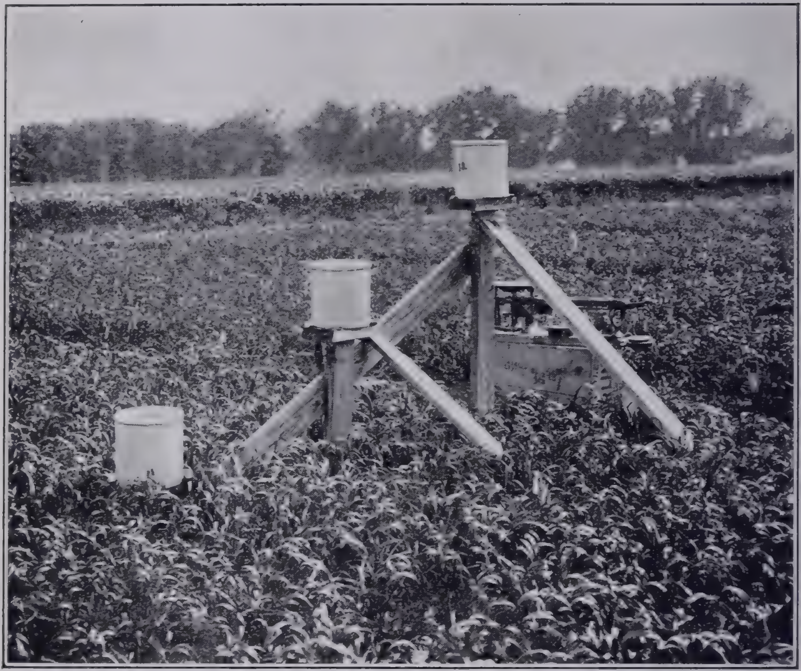

Fig. 15.—Free-water-surface evaporation jars at four elevations in an oat field. 1913. The oats have grown up around the lowest jar so that it cannot be seen in the picture. When the oats were full grown, only the upper jar showed above the plants.

moisture from the soil by surface evaporation. In 1913 the first records of evaporation at different elevations in corn were obtained when the corn had made practically no growth and the comparative evaporation rates were little affected by the surrounding crop. During the first week (Table 44) the evaporation 10 feet above the ground was 220 per cent of that on the ground surface, while at the time the corn reached maturity the upper evaporation was 430 per cent of that from the lower jar. Table 50 on page 123 summarizes the relative losses in the five tests.

RELATIVE WIND VELOCITIES 3 FEET AND 10 FEET ABOVE THE GROUND IN A CORNFIELD.

Relative wind velocities were determined during 50 days in 1914 (July 17 to September 5) at elevations of 10 feet and 3 feet above the ground in a cornfield. The movement of the wind was not obstructed at the upper elevation but was greatly retarded below by the surrounding corn. The wind gauge above the corn recorded a total wind velocity of 8,055 miles for the 50-day period, while only 521 miles were registered within the corn 3 feet above the ground. The upper wind velocity exceeded the lower fifteen times.

METHOD STUDY WITH FREE-WATER-SURFACE EVAPORATION JARS.

To secure data regarding the degree of reliability of the evaporation rates obtained from the jars used in the preceding experiments, an hourly evaporation test was made for 30 days in 1914, comparing three styles of jars. They were all 36 square inches in surface area and made of gray glazed earthenware one-half inch in thickness. They were filled uniformly to within ½ inch of the top each day, and the surfaces were freely exposed 5 feet above the ground in the cornfield. Jars Nos. 1 and 2 were of the same depth, with 10 inches of water; while No. 3 was shallow, with only 1½ inches of water. Jar No. 1 was insulated with excelsior to eliminate the heating effect of the direct rays of the sun on the outside of the jar. Nos. 2 and 3 were not insulated and stood fully exposed to the sun. Hourly temperature records were taken of the water at the surface in order to account for differences in evaporation rates. The results are contained in Table 51.

The summary indicates that the shallow jar is most sensitive and responds quickly to climatic changes. It warms more quickly in the morning and cools more quickly toward evening in response to atmospheric changes. As might be expected, the water in the deeper jars cools more slowly at night and warms more slowly in the daytime. The insulated jar remains 6° F. cooler in the heat of the day. The average day temperature of the water in the shallow jar is 1 degree cooler than the air, which compares favorably with the average transpiring leaf temperature shown in Tables 41, 42, and 43, which was 2.1° F. cooler than the air. It would appear from these figures that the shallow evaporation jar most nearly records the evaporating power of the atmosphere at any particular time, and is fairly comparable with the transpiring leaf except for some difference in exposure to the sun and wind. In comparison with the shallow jar, the deep exposed jar evaporated 15 per cent more water during the 24 hours of day and night, probably because the water remained warmer at night and cooled more slowly in the afternoon.

The results indicate that the evaporation data accompanying the daily transpiration tests reported in Tables 27 and 28 were

TABLE 51.—*Summary showing the relative responsiveness of free water surface evaporation from several styles of evaporation jars having 36 square inch surface area. (Average for 30 days.) 1914.*

Hour ending	Average evaporation			Average temperature of water			Climatic factors		
	Insulated jar	Uninsulated jar	Shallow jar	Insulated jar	Uninsulated jar	Shallow jar	Mean temperature of air	Mean relative humidity of air	Mean hourly wind velocity
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Degrees F.* (5)	*Degrees F.* (6)	*Degrees F.* (7)	*Degrees F.* (8)	*Per cent* (9)	*Miles* (10)
8 a. m....	3.7	4.4	4.8	70.1	72.1	72.8	73.6	80.2	6.0
9 "	4.5	6.7	7.7	73.1	79.4	78.6	77.9	72.8	6.9
10 "	7.0	10.0	11.6	76.7	80.5	83.5	81.7	67.1	8.0
11 "	10.7	15.0	15.0	80.3	84.9	86.9	84.8	62.7	8.2
12 "	13.0	17.0	19.2	82.9	87.6	89.1	87.5	58.5	8.7
1 p. m....	17.2	23.4	24.4	86.3	90.3	91.1	89.5	55.3	8.9
2 "	19.9	24.4	25.0	88.1	91.6	92.0	90.8	52.7	9.4
3 "	19.8	25.5	22.5	88.9	91.9	90.8	91.2	51.6	9.1
4 "	19.0	25.6	22.2	89.1	92.1	89.7	91.0	50.4	9.0
5 "	19.0	25.0	18.5	87.9	90.8	86.8	89.9	51.1	8.5
6 "	15.9	19.7	14.1	85.9	88.4	83.3	88.2	52.6	8.3
7 "	11.7	14.3	10.2	83.5	85.4	79.4	85.1	58.1	7.2
8 "	9.7	10.4	6.4	81.1	82.1	75.4	81.7	64.5	6.7
Av. for day.	13.16	17.0	15.5	82.6	85.9	84.5	85.6	59.8	8.1
Av. for night	3.6	3.9	2.3	....	....	....	72.8	81.5	6.2

fairly comparable, but that the deeper jars would not have been sufficiently sensitive to record rapid changes for correlating with hourly transpiration changes.

RELATION OF AVAILABLE SOIL MOISTURE CONTENT TO GROWTH AND WATER REQUIREMENTS OF CORN.[1]

PLAN OF THE EXPERIMENTS.

During the three years 1910, 1913, and 1914, groups of Hogue's Yellow Dent corn plants were grown in potometers with all factors uniform except the degree of available water in the soil. Potometers 16 by 36 inches in size, having the coil-watering device, illustrated on page 44, were filled anew each year with fertile surface loam from one of the Experiment Station fields. The amount of water required to saturate the soil was regarded as the amount retained by the soil after seepage from water poured on the soil surface of duplicate potometers had ceased. Thus, the soil was considered saturated when it contained all the water it would hold against percolation. The standard weight of each potometer was determined for its particular degree of soil moisture content, and this standard weight was restored each day. The potometers were weighed and the water added between 7 p. m. and 8 p. m. except in 1913, when it was added two hours earlier. By this practice the transpiration rate was low at the time of applying the water, which was in this way given time to distribute itself thruout the soil mass during the night, before heavy transpiration commenced the following day.

DEGREES OF SOIL MOISTURE MAINTAINED.

The various water contents of the soil during each year are indicated in Table 52.

The results obtained with the different per cents of relative soil saturation as used in the potometers cannot be expected to correspond exactly to the same relative saturation under field conditions. The normal water-holding capacity of soil is doubtless considerably disturbed by refilling and packing in potometers. It also varies greatly with the type of soil. Nevertheless, the data obtained in this way should serve to indicate general principles of response to variation in soil moisture. The relative effects of differences in soil moisture content also vary in dif-

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[1] References concerning the relation of transpiration to soil moisture content: Fittbogen (1873), Fortier (1902), Harris (1914), Hellriegel (1883), Il'enkov (1865), Kiesselbach (1910), Kiesselbach and Montgomery (1911), Leather (1911), Maercker (1896), Ohlmer (1908), Pfeiffer et al. (1912), Preul (1908), Schroeder (1896), Seelhorst (1899), Seelhorst and Bünger (1907), Thom (1913), Widtsoe (1909), Wilms (1899), and Willard and Humbert (1913).

TABLE 52.—*Various ways of expressing water content of soil in different degrees of saturation during three years—1910, 1913, 1914.*

No. of potometers averaged in each set (1)	Water-free soil in each potometer *Pounds* (2)	Water required to saturate soil *Pounds* (3)	Relative saturation maintained *Per cent* (4)	Per cent moisture on dry soil basis *Per cent* (5)	Total water in soil *Pounds* (6)	Available water[3] *Pounds* (7)	Per cent available water on dry-soil basis *Per cent* (8)
			1910.				
4	260	100	35	13.46	35	3.8	1.46
4	260	100	45	17.31	45	13.8	5.31
4	260	100	60	23.08	60	28.8	11.08
4	260	100	80	30.77	80	48.8	18.77
4	260	100	100	38.46	100	68.8	26.46
			1913.				
8	243	105	50	22.2	53	24	9.9
8	243	105	70	29.2	74	45	18.5
8	243	105	95	41.1	100	71	29.2
			1914.[2]				
8	236	94.3	50	20.0	47	19	8.1
8	236	94.3	70	27.9	66	38	16.1
8	236	94.3	95	38.0	90	62	26.3
8[1]	236	94.3	$\frac{2}{3}$ of 70	....	....	....	....

[1] One group of potometers in 1914 started out with 70 per cent of their water-holding capacity, but the amount of moisture was gradually reduced by adding each day only two-thirds as much water as was transpired by the plants in the constant 70 per cent relative soil saturation.

[2] Half of the potometers in each group in 1914 received an application of sheep manure which increased the water-holding capacity of the soil only 1 pound.

[3] From extensive experience with these soils, the nonavailable moisture has been estimated at 12 per cent.

ferent seasons. For example, the total dry matter produced in soil 50 per cent saturated was much below that in optimum soil moisture in 1913, while in the season of 1914 this moisture content resulted in a yield not far below the optimum. Climatic conditions were such that the free-water-surface evaporation during July and August in 1913 was only 60 per cent as great as in 1914. The difference in the climatic conditions of the two years is shown in Table 34, page 109. In 1910 the maximum total plant weight was attained at 80 per cent relative saturation, while the maximum ear weight was had with 60 per cent relative saturation. Indications are that a range of optimum moisture content may exist within the limits of which a variation does not materially affect the growth of the plant. A reduction of soil-moisture content to 45 and 35 per cent relative saturation greatly reduced the ear and total dry matter, while an increase to 95 per cent also resulted in a marked reduction in total weight and weight of ear. From these data it was concluded that a mean saturation of 70 per cent of the water-holding capacity of the soil (70 per cent relative saturation) may be regarded as an optimum condition for this soil, and was used as such in the experiments which followed.

In 1910, five different degrees of relative saturation were maintained, namely, 35, 45, 60, 80, and 100 per cent of the water-holding capacity of the soil.

During 1913 and 1914 three degrees of water content were compared, representing less than optimum, optimum, and above optimum soil moisture. These were 50, 70, and 95 per cent of the water-holding capacity, with 70 per cent as the optimum. During 1914, an unmanured and a manured group of potometers were conducted at each of these three degrees. In addition, one group of both manured and unmanured potometers was started at 70 per cent relative saturation, the same as the normal 70 per cent group, but each day only two-thirds as much water was added to each potometer as was transpired on an average by the eight plants continuously kept in 70 per cent saturated soil.

The results of all three years' tests follow in detail in Tables 53, 54, and 55, and are summarized in Tables 56, 57, and 58.

DISCUSSION OF RESULTS.

The results of the three years' tests have been summarized in Tables 56, 57, and 58. In Tables 57 and 58, the data have been assembled into three general classes, according to whether the plants were grown in optimum, less than optimum, or above optimum soil-moisture content. This necessitated averaging together for 1910 the 35, 45, and 60 per cent relative saturation

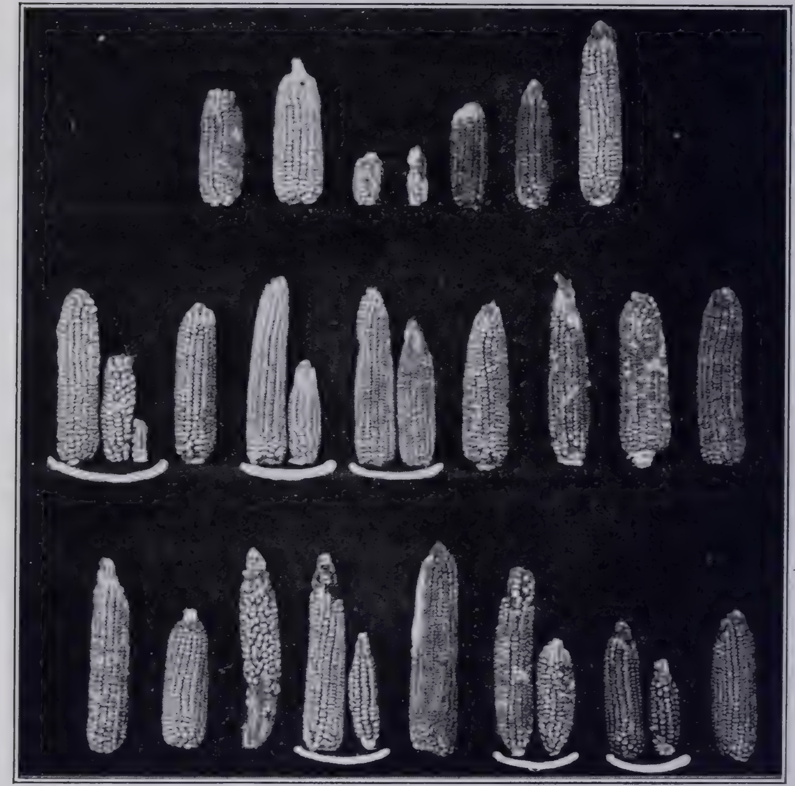

Fig. 16.—Ears grown in potometers for determining the effect of differences in soil moisture content upon growth and water requirements of the corn plant. 1913. See Table 54.
Upper row, seven potometers 50 per cent relative saturation.
Middle row, eight potometers 70 per cent relative saturation.
Bottom row, eight potometers 95 per cent relative saturation.

to represent the soil moisture below optimum. The results of this average are practically the same as for the 45 per cent relative saturation alone.

In Table 58, the results obtained under the optimum or intermediate moisture conditions are regarded as 100 per cent, and the results from the other degrees of saturation are expressed in percentages of these.

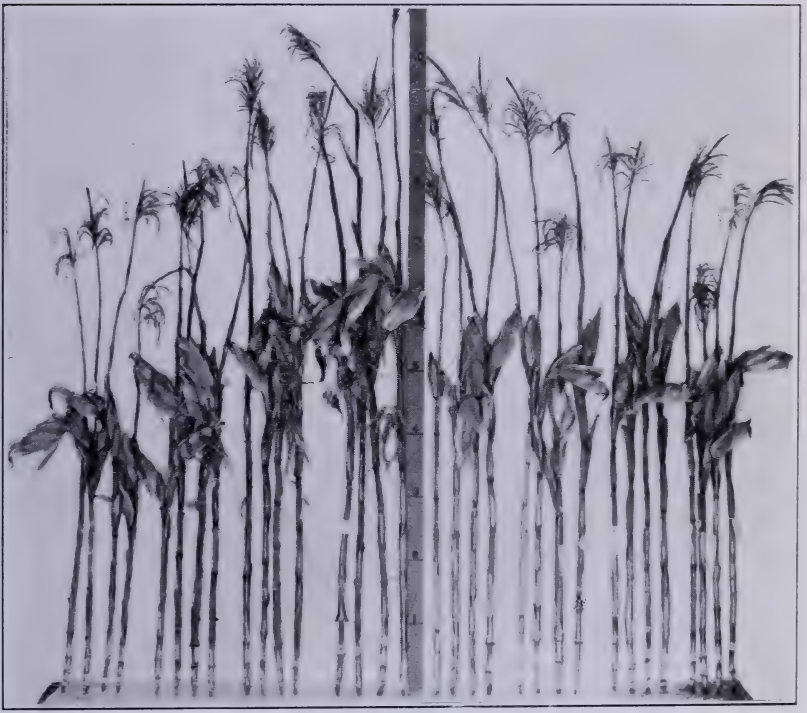

Fig. 17.—Mature plants with leaves removed grown in the four different degrees of soil saturation. 1914. Left to right: 1, 50 per cent relative soil saturation, without manure; 2, 50 per cent relative soil saturation, with manure; 3, 70 per cent relative soil saturation, without manure; 4, 70 per cent relative soil saturation, with manure; 5, 95 per cent relative soil saturation, without manure; 6, 95 per cent relative soil saturation, with manure; 7 and 8 are without and with manure, respectively, having an initial relative soil saturation of 70 per cent, which was reduced daily by supplying only two-thirds as much water as the plants in the 70 per cent relative saturation transpired each day. See Table 55.

EFFECT OF DEFICIENCY OF SOIL MOISTURE.

(THREE-YEAR AVERAGE.)

A shortage of moisture, existing in an average relative saturation of 49 per cent, decreased the moisture-free weight of stalk 37.3 per cent, the weight of ear 28.5 per cent, the weight of leaves 9.9 per cent, and the total dry matter 30.7 per cent. The total water transpired was reduced 36.8 per cent, and the leaf-area

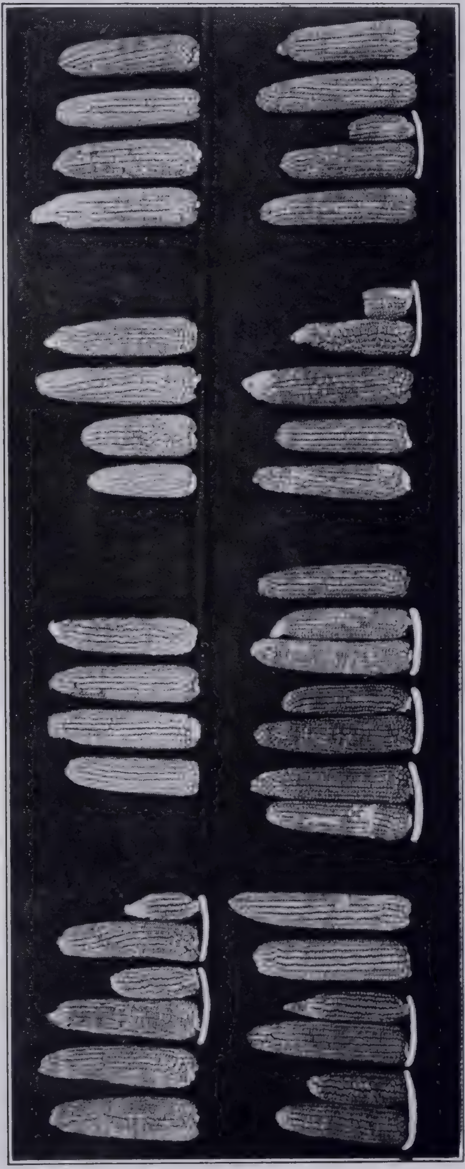

Fig. 18.—Ears grown in different degrees of soil saturation. 1914. Reading from left to right, upper row: 1, 50 per cent soil saturation; 2, 70 per cent soil saturation; 3, 95 per cent soil saturation; 4, 70 per cent soil saturation at start and reduced daily by supplying only two-thirds as much water as the eight plants in the 70 per cent soil saturation transpired each day. Lower row: Same as upper row except $1\frac{3}{4}$ pounds of moisture-free sheep manure were added to each potometer. See Table 55.

TABLE 53.—*Growth relationships and water requirements of corn in five different degrees of soil moisture. 1910.*[1]

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
THIRTY-FIVE PER CENT RELATIVE SATURATION												
71	41.6	93.9	25.5	161.0	35.139	862	374.21	218.3	40.8	5.4	2.3	60
72	38.5	43.5	27.0	109.0	25.310	896	581.8	232.2	28.2	8.2	1.1	42
73	38.4	17.0	22.4	77.8	22.845	741	1,343.8	293.6	30.8	9.5	.4	46
74	51.8	16.0	30.6	98.4	29.392	913	1,837.0	298.7	32.2	9.3	.3	56
Average....	42.6	42.6	26.4	111.5	28.171	853	661.3	252.6	33.0	7.7	1.0	51
FORTY-FIVE PER CENT RELATIVE SATURATION												
75	94.6	180.4	42.1	317.1	76.998	1,071	426.8	242.8	71.9	3.4	1.9	72
76	90.6	104.7	39.3	234.6	57.399	1,244	548.2	244.6	46.1	5.3	1.2	70
77	113.1	196.1	43.7	352.9	79.264	1,403	404.2	224.6	56.5	4.0	1.7	83
78	89.8	155.5	38.7	284.0	58.993	1,126	379.4	207.7	52.4	4.0	1.7	75
Average....	97.0	159.2	40.9	297.1	68.163	1,211	428.2	229.4	56.3	4.1	1.6	75
SIXTY PER CENT RELATIVE SATURATION												
79	129.1	253.9	38.8	421.8	88.121	951	347.1	208.9	92.6	2.3	2.0	88
80	190.6	247.9	38.0	476.5	108.923	1,308	439.4	228.6	83.3	2.7	1.3	94
81	156.6	218.4	51.0	426.0	112.583	1,366	515.5	264.3	82.4	3.2	1.4	87
82	161.5	255.7	30.5	447.7	113.237	1,198	442.9	252.9	94.5	2.7	1.6	101
Average....	158.4	244.0	39.6	443.0	105.716	1,206	433.3	238.6	87.7	2.7	1.5	93
EIGHTY PER CENT RELATIVE SATURATION												
83	218.7	216.2	38.0	472.9	134.311	1,447	621.2	284.0	92.8	3.1	1.0	120
84	270.1	271.4	64.7	606.2	153.324	1,804	564.9	252.9	85.0	3.0	1.0	98
85	180.2	255.5	38.4	474.1	123.107	1,125	481.8	259.7	109.4	2.4	1.4	89
86	153.8	203.4	26.0	383.2	97.565	875	479.7	254.6	111.5	2.3	1.3	96
Average....	205.7	236.6	41.8	484.1	127.077	1,313	537.1	262.5	96.8	2.7	1.2	101
ONE HUNDRED PER CENT RELATIVE SATURATION												
87	166.9	205.0	35.3	407.2	115.806	1,268	564.9	284.4	91.3	3.1	1.2	108
88	160.4	200.0	32.5	392.9	112.624	986	563.1	286.6	114.2	2.5	1.2	92
89	137.6	148.5	32.1	318.2	95.612	1,072	643.9	300.5	89.2	3.4	1.1	100
Average....	155.0	184.5	33.3	372.8	108,014	1,109	585.4	289.7	97.4	3.0	1.2	100

[1] Kiesselbach, T. A., and Montgomery, E. G., 1911, give a summary of the 1910 results.

TABLE 54.—*Growth relationships and water requirements of corn in three different degrees of soil moisture. 1913.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
FIFTY PER CENT RELATIVE SATURATION												
9	96	120	36	252	95.703	839	797.52	379.77	114.07	3.33	1.25	69
10	95	203	26	324	105.146	696	517.96	324.52	151.07	2.15	2.14	72
11	134	No ear	38	172	86.759	824	....	504.41	105.29	4.79	....	66
12	79	5	29	113	50.825	743	10,165.00	449.77	68.42	6.58	.06	69
13	98	88	28	214	76.681	687	871.38	358.32	111.62	3.21	.90	66
15	78	109	31	218	69.644	784	638.94	319.47	88.83	3.60	1.40	72
16	108	194	42	344	115.588	871	595.81	336.01	132.71	2.53	1.80	77
Average....	98.29	102.71	32.86	233.86	85.764	777.71	835.01	366.73	110.28	3.32	1.04	70
SEVENTY PER CENT RELATIVE SATURATION												
17	181	253	47	481	195.447	1,175	772.52	406.33	166.34	2.44	1.40	108
18	108	162	26	296	126.121	962	778.52	426.08	131.10	3.25	1.50	108
19	103	239	31	373	123.488	741	516.69	331.07	166.65	1.99	2.32	90
20	128	251	32	411	145.666	907	580.34	354.42	160.60	2.21	1.96	84
21	178	199	38	415	163.349	887	820.85	393.61	184.16	2.14	1.12	96
22	231	153	49	433	190.862	1,145	1,274.46	440.79	166.69	2.64	.66	108
23	134	237	35	406	143.623	849	606.00	353.75	169.17	2.09	1.77	90
24	166	233	47	446	163.781	901	702.92	367.22	181.78	2.02	1.40	90
Average....	153.62	215.88	38.13	407.63	156.542	945.88	725.15	384.00	165.50	2.32	1.41	97
NINETY-FIVE PER CENT RELATIVE SATURATION												
1	192	151	35	378	169.569	1,059	1,122.97	448.60	160.12	2.80	.79	108
2	116	152	32	300	134.498	775	884.86	448.33	173.55	2.58	1.31	102
3	201	98	28	327	168.888	1,008	1,723.34	516.48	167.55	3.08	.49	108
4	147	213	30	390	154.746	897	726.51	396.78	172.52	2.30	1.45	90
5	157	238	30	425	156.970	890	659.54	369.34	176.37	2.09	1.52	90
6	168	225	34	427	168.752	918	750.00	395.20	183.83	2.15	1.34	96
7	213	173	47	433	184.165	1,000	1,064.54	425.32	184.17	2.31	.81	96
8	117	150	29	296	136.768	853	911.79	462.05	160.34	2.88	1.28	90
Average....	163.88	175.00	33.12	372.00	159.294	925.00	910.25	428.21	172.21	2.49	1.07	98

TABLE 55.—*Growth relationships and water requirements of corn in four different degrees of soil moisture, with and without manure. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
FIFTY PER CENT RELATIVE SATURATION												
1	167	302	42	511	142.286	1,164	471.13	278.45	122.24	2.28	1.81	82
2	199	278	52	529	151.366	1,727	544.45	286.07	87.65	3.26	1.40	96
3	160	326	41	527	147.779	1,360	453.31	280.42	108.66	2.58	2.04	89
4	150	291	40	481	128.053	1,379	440.05	266.22	92.86	2.87	1.94	92
Average....	169.00	299.25	43.75	512.00	142.371	1,407.50	475.76	278.07	101.15	2.75	1.77	90
FIFTY PER CENT RELATIVE SATURATION WITH MANURE												
5	255	350	42	647	171.002	1,163	488.55	264.30	147.04	1.80	1.37	96
6	211	363	48	622	174.883	1,541	481.77	281.16	113.49	2.48	1.72	96
7	265	323	48	636	159.901	1,305	495.08	251.41	122.53	2.05	1.22	105
8	242	286	46	574	148.211	1,208	518.22	258.21	122.69	2.10	1.18	105
Average....	243.25	330.50	46.00	619.75	163.498	1,304.25	494.70	263.81	125.38	2.10	1.36	101
SEVENTY PER CENT RELATIVE SATURATION												
9	271	232	38	541	169.605	1,475	731.06	313.50	114.98	2.73	.86	116
10	275	255	43	573	170.536	1,170	668.77	297.62	145.78	2.04	.93	112
11	249	272	45	566	169.605	1,322	623.55	299.66	128.23	2.34	1.09	114
12	286	230	46	562	173.283	1,765	753.43	308.33	98.18	3.14	.80	108
Average....	270.25	247.25	43.00	560.50	170.757	1,433.00	690.62	304.62	119.16	2.56	.92	113
SEVENTY PER CENT RELATIVE SATURATION WITH MANURE												
13	260	468	47	775	225.107	1,501	481.00	290.46	149.97	1.94	1.80	117
14	256	406	48	710	209.807	1,532	516.77	295.50	136.95	2.16	1.59	122
15	246	329	65	640	188.946	1,536	574.31	295.28	123.01	2.40	1.34	127
16	307	232	33	572	188.265	1,382	811.47	329.12	136.23	2.42	.76	126
Average....	267.25	358.75	48.25	674.25	203.031	1,487.75	565.95	301.11	136.47	2.21	1.34	123

TABLE 55 CONTINUED.—*Growth relationships and water requirements of corn in four different degrees of soil moisture, with and without manure. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
NINETY-FIVE PER CENT RELATIVE SATURATION												
17	123	160	31	314	120.932	1,208	755.81	385.11	100.11	3.85	1.30	98
18	259	241	39	539	165.152	1,321	685.28	306.41	125.02	2.45	.93	122
19	220	297	46	563	160.657	1,541	540.94	285.36	104.26	2.74	1.35	113
20	237	255	45	537	169.465	1,527	664.57	315.52	110.98	2.84	1.08	95
Average....	209.75	238.25	40.25	488.25	154.051	1,399.25	646.59	315.52	110.10	2.87	1.14	107
NINETY-FIVE PER CENT RELATIVE SATURATION WITH MANURE												
21	136	218	34	388	136.982	1,248	628.35	353.05	109.76	3.22	1.60	115
22	289	220	53	562	150.533	1,248	684.24	267.85	120.62	2.22	.76	114
23	227	313	36	576	169.955	1,099	542.99	295.06	154.64	1.91	1.38	115
24	326	178	50	554	178.022	1,350	1,000.12	321.34	131.86	2.44	.55	96
Average....	244.50	232.25	43.25	520.00	158.873	1,236.25	684.06	305.53	128.51	2.38	.95	110
RELATIVE SATURATION EQUAL TO 70 PER CENT AT START, AND REDUCED DAILY BY ONE-THIRD OF AVERAGE DAILY TRANSPIRATION OF THE OTHER 70 PER CENT GROUP (POTOS. 9-16).												
25	184	276	31	491	128.641	1,114	466.09	262.00	115.48	2.27	1.50	108
26	214	280	42	536	128.391	1,371	458.54	239.53	93.65	2.56	1.31	106
27	212	226	31	469	128.459	1,204	568.58	273.90	106.69	2.57	1.07	112
28	196	239	39	474	129.458	1,201	541.68	273.10	107.79	2.53	1.22	....
Average....	201.50	255.25	35.75	492.50	128.737	1,22.50	504.326	261.40	105.31	2.48	1.27	109
RELATIVE SATURATION EQUAL TO 70 PER CENT AT START, AND REDUCED DAILY BY ONE-THIRD OF AVERAGE DAILY TRANSPIRATION OF THE OTHER 70 PER CENT GROUP (POTOS. 9-16), WITH MANURE												
29	209	235	38	482	128.119	1,074	545.23	265.81	119.29	2.23	1.12	104
30	189	273	38	500	125.486	1,155	459.63	250.97	108.63	2.31	1.44	102
31	198	259	39	496	128.187	1,089	494.94	258.43	117.70	2.20	1.31	97
32	208	247	40	495	127.960	1,103	518.06	258.50	116.01	2.23	1.19	81
Average....	201.00	253.50	38.75	493.25	127.438	1,105.25	502.71	258.37	115.30	2.24	1.26	96

TABLE 56.—*Summary showing the growth relationships and water requirements of corn in different degrees of soil moisture, during three years—1910, 1913, 1914.*

Relative saturation	No. of potos. averaged	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
		Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
Per cent (1)	(2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Grams* (6)	*Kilograms* (7)	*Sq. in.* (8)	*Grams* (9)	*Grams* (10)	*Grams* (11)	*Sq. in.* (12)	(13)	*Inches* (14)
YEAR 1910													
35	4	42.6	42.6	26.4	111.5	28.171	853	661.3	252.6	33.0	7.7	1.0	51
45	4	97.0	159.2	40.9	297.1	68.163	1,211	428.2	229.4	56.3	4.1	1.6	75
60	4	158.4	244.0	39.6	443.0	105.716	1,206	433.2	238.6	87.7	2.7	1.5	93
80	4	205.7	236.6	41.8	484.1	127.077	1,313	537.1	262.5	96.8	2.7	1.2	101
100	3	155.0	184.5	33.3	372.8	108.014	1,109	585.4	289.7	97.4	3.0	1.2	100
YEAR 1913													
50	7	98.29	102.71	32.86	233.86	85.764	777.71	835.01	366.73	110.28	3.32	1.04	70
70	8	153.62	215.88	38.13	407.63	156.542	945.88	725.15	384.00	165.50	2.32	1.41	97
95	8	163.88	175.00	33.12	372.00	159.294	925.00	910.25	428.21	172.21	2.49	1.07	98
YEAR 1914													
50	4	169.00	299.25	43.75	512.00	142.371	1,407.50	475.76	278.07	101.15	2.75	1.77	90
50[1]	4	243.25	330.50	46.00	619.75	163.498	1,304.25	494.70	263.81	125.38	2.10	1.36	101
70	4	270.25	247.25	43.00	560.50	170.757	1,433.00	690.62	304.62	119.16	2.56	.92	113
70[1]	4	267.25	358.75	48.25	674.25	203.031	1,487.75	565.95	301.11	136.47	2.21	1.34	123
95	4	209.75	238.25	40.25	488.25	154.051	1,399.25	646.59	315.52	110.10	2.87	1.14	107
95[1]	4	244.50	232.25	43.25	520.00	158.873	1,236.25	684.06	305.53	128.51	2.38	.95	110
⅔ of 70	4	201.50	255.25	35.75	492.50	128.737	1,222.50	504.36	261.40	105.31	2.48	1.27	109
⅔ of 70[1]	4	201.00	253.50	38.75	493.25	127.438	1,105.25	502.71	258.37	115.30	2.24	1.26	96

[1] With 1.75 pounds of moisture-free sheep manure added.

TABLE 57.—*Summary of three years' results with different degrees of soil-moisture content—1910, 1913, 1914. (The data in Table 56 are here assumed so as to throw all results into three classes, namely: 1. Less than optimum, 2. optimum, 3. above optimum soil-moisture content.)*[1]

Year	Relative saturation	No. of potos. averaged	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
			Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Lbs.* (2)	(3)	*Grams* (4)	*Grams* (5)	*Grams* (6)	*Grams* (7)	*Kilograms* (8)	*Sq. in.* (9)	*Grams* (10)	*Grams* (11)	*Grams* (12)	*Sq. in.* (13)	(14)	*Inches* (15)
LOW RELATIVE SATURATION														
1910[2]..	47	12	99	149	36	284	67.35	1,090	508	240	59	4.8	1.4	73
1913..	50	7	98	103	33	234	85.76	778	835	367	110	3.3	1.0	70
1914[3]..	50	8	206	315	45	566	152.94	1,356	485	271	113	2.4	1.6	95
Av....	49	27	134	189	38	361	102.02	1,075	609	293	94	3.5	1.3	79
MEDIUM RELATIVE SATURATION														
9110..	80	4	206	237	42	484	127.08	1,313	537	263	97	2.7	1.2	101
1913..	70	8	154	216	38	408	156.54	946	725	384	166	2.3	1.4	97
1914[3]..	70	8	269	303	46	617	186.90	1,460	628	303	128	2.4	1.1	118
Av....	73	20	210	252	42	503	156.84	1,240	630	317	130	2.5	1.2	105
HIGH RELATIVE SATURATION														
1910..	100	3	155	185	33	373	108.01	1,109	585	290	97	3.0	1.2	100
1913..	95	8	164	175	33	372	159.29	925	910	428	172	2.5	1.1	98
1914[3]..	95	8	227	235	42	504	156.46	1,318	665	311	119	2.6	1.0	108
Av....	97	19	182	198	36	416	141.25	1,117	720	343	129	2.7	1.1	102

[1] For discussion of method used in compiling averages for two or more years, see page 42.

[2] Average of 35, 45, and 60 per cent relative saturation.

[3] Average of plants with and without manure.

TABLE 58.—*Summary of three years' results with different degrees of soil-moisture content. (The results in Table 57 are here expressed in per cent of the optimum condition.)*

Year	Relative saturation	No. of potos. averaged	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
			Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*P.ct.* (2)	(3)	*Per cent* (4)	*Per cent* (5)	*Per cent* (6)	*Per cent* (7)	*Per cent* (8)	*Per cent* (9)	*Per cent* (10)	*Per cent* (11)	*Per cent* (12)	*Per cent* (13)	*Per cent* (14)	*Per ct.* (15)
LOW RELATIVE SATURATION														
1910...	47	12	48.0	62.9	85.7	58.7	53.0	83.0	94.6	91.3	60.8	177.8	116.7	72.3
1913...	50	7	63.6	47.7	86.8	57.4	54.8	82.2	115.2	95.6	66.3	143.5	71.4	72.2
1914...	50	8	76.6	104.0	97.9	91.7	81.8	92.9	77.2	89.4	88.3	100.0	145.5	80.5
Av....	49	27	62.7	71.5	90.1	69.3	63.2	86.0	95.7	92.1	71.8	140.4	111.2	75.0
MEDIUM RELATIVE SATURATION														
1910...	80	4	100	100	100	100	100	100	100	100	100	100	100	100
1913...	70	8	100	100	100	100	100	100	100	100	100	100	100	100
1914...	70	8	100	100	100	100	100	100	100	100	100	100	100	100
Av....	73	20	100	100	100	100	100	100	100	100	100	100	100	100
HIGH RELATIVE SATURATION														
1910...	100	3	75.2	78.1	78.6	77.1	85.0	84.5	109.0	110.5	100.0	111.1	100.0	99.0
1913...	95	8	106.5	81.0	86.8	91.2	101.8	97.8	125.5	111.4	103.6	108.7	78.6	101.0
1914...	95	8	84.4	77.6	91.3	81.7	83.7	90.3	105.9	102.6	93.0	108.3	90.9	91.5
Av....	97	19	88.7	78.9	85.6	83.3	90.2	90.9	113.5	108.2	98.9	109.4	89.8	97.2

14 per cent. The water used per gram dry weight of ear was reduced 4.3 per cent, per gram total dry matter 7.9 per cent, and per square inch leaf-area 28.2 per cent. The ratio of leaf-area to dry matter was 40.4 per cent greater and the ratio of weight of ear to weight of stalk was 11.2 per cent greater in the deficient moisture content than in the optimum. The height of plants also was reduced 26 inches, or 25 per cent.

At first thought it would appear that a greater efficiency in the use of water had been effected by a reduction of the soil moisture below the optimum. However, a saving of 7.9 per cent in the water requirement per unit total dry matter, and 4.3 per cent in the water requirement per unit weight of ear, was accomplished only thru a reduction of 30.7 per cent in the yield of dry matter and 28.5 per cent in the weight of ears. Consequently, a reduction of soil-moisture content below the optimum would not be practicable in order to bring about a saving in the water requirement per unit dry matter.

It is clear that the efficiency of the leaves in elaborating dry matter is reduced with a deficiency of soil moisture, the average increase in leaf-area per unit dry matter being 40 per cent in these experiments. This is probably due to a relatively more normal growth up to the time of full leaf development, followed by a retardation of growth caused by excessive evaporation demands occurring during August and the latter half of July.

The reduction of 28.2 per cent in the water loss per unit leaf-area would perhaps appear to support the old theory that the leaf stomata exert a regulative control by partial closing when a deficiency of soil moisture exists. However, it must be borne in mind that these plants were doubtless less exposed to evaporation influences, being 26 inches less in height. The free-water-surface evaporation data in Table 50, page 123, show an average reduction of 17 per cent in the evaporation rate with an average reduction of 23 inches in elevation in a cornfield from 84 inches to 61 inches. During the two years 1910 and 1913, the plants also grew slowly and the maximum leaf development did not occur until somewhat later than with the optimum soil moisture. This reduced the length of time during which the total leaf-area evaporated water, and thus reduced slightly the relative water loss per square inch leaf-area. The close correlation between the hourly and daily transpiration and evaporation rates in relation to climatic factors shown earlier in this bulletin also fails to support the theory of stomatic control. If there was an inherent reduction in the transpiration rate per unit leaf-area aside from the influences mentioned above, it was perhaps due to a lower water content or lessened turgidity of the leaves. It is a principle in physics that water evaporates less freely from a partially saturated object than from one fully saturated. A slight wilting also occurred, in a few instances. This may actually reduce transpiration by stomatic closure due to a physical collapse of the tissues rather than thru regulative closure.

An examination of stomata in wilted leaves has shown them to be practically closed as compared with open stomata in a turgid leaf at the same time.

Future studies may throw more definite light upon these speculative observations.

EFFECT OF AN OVERABUNDANCE OF SOIL MOISTURE.

(THREE-YEAR AVERAGE.)

An overabundance of soil moisture, existing in an average relative saturation of 97 per cent, decreased the moisture-free weight of stalk 11.3 per cent, the weight of ear 21.1 per cent, the weight of leaves 14.4 per cent, the total dry matter 16.7 per cent, the total water transpired 9.8 per cent, and the total leaf-area 9.1 per cent. The water used per gram dry weight of ear was increased 13.5 per cent, per gram total dry matter 8.2 per cent. The water used per unit leaf-area was reduced 1.1 per cent. The ratio of leaf-area to dry matter was 9.4 per cent greater, and the ratio of ear weight to stalk weight 11.2 per cent lower. The average height of plant was nearly normal, being reduced 2.8 per cent, or 3 inches.

From such data as these, showing an increase in the water requirement per unit weight of dry matter, investigators have rather generally concluded that the plant in some way releases a control over the transpiration rate, and that the plant strives to get rid of the surplus water by increased transpiration. It has been frequently said that less work is required by the plant to absorb moisture from a saturated soil, and that it is therefore used more extravagantly. The writer, however, believes that no consideration of a vital element on the part of the plant need enter into an interpretation. It appears more probable that the water requirement per unit dry matter is increased because of a reduction in the available fertility due to surplus water in the soil. Toward the end of the season the lower leaves of the plants usually show symptoms of a lack of nitrogen. An average reduction of 16.7 per cent in the dry weight of the plant supports this interpretation.

EFFECT OF INCREASING THE FERTILITY OF SOILS DIFFERING IN MOISTURE CONTENT.

In 1914 (Table 56) half of the potometers in each degree of soil moisture received an application of 1.75 pounds of well-rotted moisture-free sheep manure per plant, which is at the rate of 9.3 tons per acre, counting 10,668 plants per acre grown three per hill, with hills 3.5 feet apart. The object was to note the effect of increasing the fertility of soils differing only in their water content. One frequently reads the statements that: As a principle in dry farming, a shortage of moisture may be offset by an increase in soil fertility thru manure or other fertilizer; to a certain extent, manure may take the place of water; and a field of grain may be grown with actually less rainfall if the soil fertility is increased, even tho the soil is fertile to begin with, as are most soils of the Great Plains area of the United States.

No definite conclusions may be drawn from the single test reported here concerning this interrelationship, for the reason that the lowest relative saturation employed proved little inferior to the optimum moisture content—due to the low atmospheric evaporation values of the particular season. The application of the manure to the soil with a shortage of moisture increased the yield of dry matter 21 per cent, and also increased the total water used per plant 14 per cent and the water used per square inch leaf-area 24 per cent. (The increased transpiration per unit leaf-area when manure was applied was probably partially due to a healthier condition of the lower leaves during the latter half of the growing season.) The water requirement per unit dry matter was reduced 5 per cent. The application of manure affected the results in very much the same manner in the optimum (70 per cent) and the overabundant (95 per cent) soil moisture, as may be seen from a study of Table 56 for 1914.

The plants which started out in 1914 with an optimum (70 per cent) amount of moisture and received each day thereafter only two-thirds as much water as was transpired by the average of eight plants in soil constantly 70 per cent saturated, were reduced 14 per cent in yield of dry matter. With these plants, the manure failed to affect in a material degree any of the important growth or transpiration relationships, as is summarized in Table 56. Other data indicate that probably different results would be secured under such conditions as prevailed in 1913, when moisture was a great limiting factor with those plants in the lowest saturation. This problem of the effect of increasing the fertility where a marked shortage of moisture exists will be further investigated in future experiments.

RELATION OF SOIL FERTILITY TO GROWTH AND WATER REQUIREMENTS OF CORN.[1]

Two different series of soil fertility potometers have been operated and are reported in this paper. (1) The first of these was started in 1911, one year's results having been published.[2] The soil used in the initial filling of the potometers in 1911 has remained undisturbed thruout the past four years. A crop of corn has been harvested from it each year, and the yields and water requirements have been determined. (2) The second series was commenced in 1914, and was similar in plan to series No. 1 except in the degree of soil fertility.

In each experiment three soils were used, representing low, medium, and high fertility. Eight duplicate potometers of the subirrigation type were filled with each kind of soil, four of which received an application of well-rotted sheep manure, thoroly mixed with the upper 10 inches of soil. The other four potometers of each group remained untreated. Manure was applied in both experiments at the rate of 4 pounds per potometer, which was equivalent to approximately 21 tons per acre, wet weight, counting 10,668 plants per acre grown three per hill, with hills 3.5 feet apart. Reduced to a moisture-free basis, this manure application was 2.4 pounds per plant in 1911 and 1.75 pounds in 1914, which equaled respectively 13 tons and 9 tons of moisture-free manure per acre.

The average composition of the different soils used is given in Table 59, while the total amount of plant food elements contained in each potometer is given in Table 60.

The soils may be briefly described as follows:

(1) Infertile soil. This has been classified as Lancaster Fine Sandy Loam, and was taken from a cornfield of low productivity five miles distant from the Agricultural Experiment Station.

In the 1911 experiment the soil was refilled in the potometers in 6-inch layers as they were taken from the soil, while in 1914 only the surface 10 inches of soil was used.

(2) Fertile soil. This was Wabash silt loam taken in 6-inch layers in 1911 from a native pasture of the Agricultural Experi-

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[1] References concerning the relation of transpiration to soil fertility: Briggs and Shantz (1914), Heinrich (1894), Hellriegel (1883), Kiesselbach (1910), King (1893, 1894), Lawes (1850), Leather (1910, 1911), Liebscher (1895), Maercker (1896), Marié-Davy (1874, 1875, and 1876), Montgomery and Kiesselbach (1912), Ohlmer (1908), Pfeiffer et al. (1912), Preul (1908), Schroeder (1896), Seelhorst (1899, 1906, 1907, 1910), Seelhorst and Bünger (1907), Sorauer (1883), Thom (1913), Widtsoe (1909), Wilfarth and Wimmer (1902), Wilms (1899), Wimmer (1908), and Willard and Humbert (1913).

[2] Montgomery and Kiesselbach (1912).

TABLE 59.—*Summary of average analyses*[1] *of soils used in filling the potometers in the soil fertility series in 1911 and 1914.*

Type of soil	Without manure				With manure				
	Weight of dry soil (moisture-free)	Total nitrogen N	Acid soluble potash K_2O	Acid soluble phosphoric acid P_2O_5	Weight of dry soil and manure (moisture-free)	Weight of manure added (moisture-free)	Total nitrogen N	Acid soluble potash K_2O	Acid soluble phosphoric acid
	Pounds (1)	*Per cent* (2)	*Per cent* (3)	*Per cent* (4)	*Pounds* (5)	*Pounds* (6)	*Per cent* (7)	*Per ct.* (8)	*Per cent* (9)
YEAR 1911									
Infertile	315	.056	.330	.050	317.4	2.4	.070	.335	.064
Intermediate	301	.077	.350	.047	303.4	2.4	.090	.360	.063
Fertile	230	.193	.697	.087	232.4	2.4	.210	.705	.106
YEAR 1914									
Infertile	302	.100	.260	.090	303.75	1.75	.111	.267	.101
Intermediate	271	.160	.420	.140	272.75	1.75	.172	.424	.152
Fertile	240	.220	.580	.200	241.75	1.75	.233	.587	.213
YEAR 1911 AND 1914									
Manure used		2.08	1.55	2.02					

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[1] For methods of analyses see Bul. 111, Nebraska Experiment Station. The analyses were made under the direction of Dr. F. J. Alway, Station Chemist, in 1911. The analyses in 1914 were made under the direction of Dr. F. W. Upson, Chemist of the Station.

TABLE 60.—*Total amount, in pounds, of nitrogen, acid soluble potash, and phosphoric acid contained in the soil of the average potometer in each group of the fertility series. 1911 and 1914.*

Type of soil	Plant food elements in each potometer					
	Without manure			With manure		
	N	Acid soluble		N	Acid soluble	
		K_2O	P_2O_5		K_2O	P_2O_5
	Pounds (1)	*Pounds* (2)	*Pounds* (3)	*Pounds* (4)	*Pounds* (5)	*Pounds* (6)
YEAR 1911						
Infertile	0.177	1.039	0.157	0.222	1.063	0.203
Intermediate	.232	1.054	.142	.273	1.092	.191
Fertile	.444	1.603	.200	.498	1.638	.246
YEAR 1914						
Infertile	.302	.785	.272	.337	.811	.307
Intermediate	.433	1.138	.379	.469	1.156	.414
Fertile	.528	1.392	.480	.563	1.419	.515

ment Station. In 1914 the surface 10 inches of a similar soil was taken from an adjoining productive cornfield.

(3) Intermediate fertile soil. This soil was prepared in 1911 by filling the bottom two feet of the potometer with the 2d and 3d foot of the infertile soil; and for the upper foot an equal mixture of the surface foot of the infertile and fertile soils was used. In 1914 a uniform mixture was prepared by combining equal weights of the infertile and fertile soil. An intermediate stage of fertility was evidently secured each year, since in comparison with the infertile and fertile soils, the yields of dry matter were respectively 113, 184, and 270 grams in 1911 and 142, 330, and 417 in 1914. The higher yields in 1914 are due in large part to the fact that only surface soil was used.

RESULTS OF THE TWO SOIL FERTILITY EXPERIMENTS. 1911 AND 1914.

The soils placed in the potometers in 1911 evidently deteriorated after the first year, because the plants have each year since acquired a yellowish color and have been comparatively unproductive. Altho the data for the last three years from these soils are summarized in Table 66, the results must be regarded as abnormal. They are given more to show the possible deteriorating effect on soil of long confinement in cans.

The individual plant data obtained in 1911, and those from the new series commenced in 1914, are given in detail in Tables 61 and 62 and are summarized in Tables 63 and 64. The plants grown during these two years were entirely normal, according to the fertility of the soil. Figures 19 and 20 show the actual ears grown in the 1911 and 1914 fertility experiments.

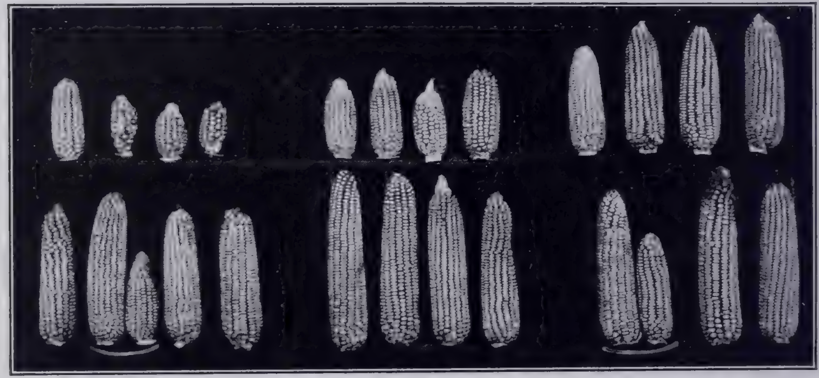

Fig. 19.—Ears harvested from the 23 plants in fertility series of 1911 grouped according to soil fertility, as follows, reading from left to right—Upper row—1, infertile soil; 2, medium soil; 3, fertile soil. Lower row—4, infertile soil plus manure; 5, medium soil plus manure; 6, fertile soil plus manure. See Table 61.

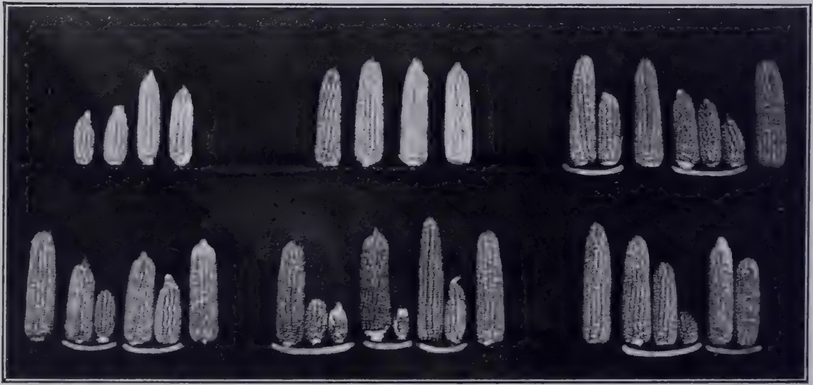

Fig. 20.—Ears harvested from the new fertility series started in 1914. Grouped from left to right according to soil fertility: Upper row—1, infertile soil; 2, intermediate soil; 3, fertile soil. Lower row—4, infertile soil, with manure; 5, intermediate soil, with manure; 6, fertile soil, with manure (3 plants). See Table 62.

TABLE 61.[1]—*Summary of data secured from potometers containing soils of six degrees of fertility. 1911.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
					INFERTILE SOIL							
1	51.17	67.42	14.31	132.90	69.131	459	1,025.38	520.18	150.0	3.45	1.32	66
2	79.39	22.08	13.33	114.80	59.519	479	2,695.61	518.46	124.3	4.17	.28	69
3	43.23	38.78	15.31	97.32	56.323	481	1,452.37	578.74	117.1	4.94	.90	62
4	71.39	18.68	15.92	105.99	62.870	487	3,365.63	593.17	129.1	4.59	.26	76
Average....	61.29	36.74	14.72	112.75	61.961	476.50	1,686.47	549.50	130.0	4.23	.60	68
					INFERTILE SOIL WITH MANURE							
5	110.57	165.53	22.71	298.81	105.673	782	638.39	353.64	135.1	2.62	1.50	87
6	146.02	203.00	36.23	385.25	136.304	1,072	671.45	353.81	127.1	2.78	1.39	87
7	162.07	246.23	39.22	447.52	143.092	1,066	581.13	319.74	134.2	2.38	1.52	87
8	180.20	161.20	30.30	371.70	141.544	1,001	878.06	380.80	141.4	2.69	.89	108
Average....	149.71	193.99	32.11	375.82	131.653	980.25	678.66	350.30	134.3	2.61	1.30	92
					INTERMEDIATE SOIL							
9	87.04	72.02	17.02	176.08	82.274	601	1,142.38	467.25	136.9	3.41	.83	83
10	86.98	79.00	20.33	186.31	87.627	607	1,109.20	470.33	144.3	3.26	.91	78
11	85.18	63.42	15.40	164.00	89.088	741	1,404.73	543.22	120.2	4.52	.74	83
12	96.95	95.50	18.72	211.17	94.237	597	986.77	446.26	157.9	2.83	.99	81
Average....	89.04	77.48	17.87	184.39	88.306	636.50	1,139.73	478.90	138.8	3.45	.87	81

[1] Montgomery, E. G., and Kiesselbach, T. A., 1912, report the 1911 data.

TABLE 61 CONTINUED.—*Summary of data secured from potometers containing soils of six degrees of fertility. 1911.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
INTERMEDIATE SOIL WITH MANURE												
13	120.65	221.30	26.47	368.42	128.069	734	578.71	347.62	174.5	1.99	1.83	90
14	152.52	223.57	27.34	403.43	142.424	902	637.04	353.03	157.8	2.24	1.47	96
15	211.89	223.91	36.70	472.50	155.926	1,005	696.38	330.00	155.2	2.13	1.05	95
16	203.37	170.40	36.40	410.17	137.898	919	809.26	336.20	150.1	2.24	.84	86
Average....	172.11	209.79	31.73	413.63	141.079	890.00	672.48	341.10	158.5	2.15	1.22	92
FERTILE SOIL												
17	116.87	105.63	20.31	242.81	101.337	644	959.36	417.35	157.3	2.65	.90	88
18	110.72	155.52	24.84	291.08	108.955	588	700.59	374.31	185.3	2.02	1.40	79
19	110.15	126.88	20.75	257.78	101.197	724	797.58	392.58	139.8	2.81	1.15	82
20	105.95	151.07	30.69	287.71	111.870	797	740.52	388.83	140.4	2.77	1.43	84
Average....	110.92	134.77	24.15	269.85	105.840	688.25	785.34	392.22	153.8	2.55	1.22	83
FERTILE SOIL WITH MANURE												
22	234.02	310.65	45.77	590.44	197.558	1,100	635.95	334.59	179.6	1.86	1.33	99
23	212.52	237.65	39.93	490.10	170.695	1,101	718.26	348.29	155.0	2.25	1.12	95
24	134.65	177.34	25.12	337.11	122.802	777	692.47	364.22	158.0	2.31	1.32	91
Average....	193.73	241.88	36.94	472.55	163.685	992.7	676.72	346.40	164.9	2.10	1.25	95

TABLE 62.—*Summary of data secured from potometers containing soils of six degrees of fertility. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
INFERTILE SOIL												
14	65	48	18	131	49.450	496	1,030.20	377.48	99.69	3.79	.74	87
15	66	61	18	145	62.420	599	1,023.28	430.48	104.21	4.13	.92	89
42	53	93	14	160	51.350	473	552.15	320.94	108.56	2.96	1.75	68
43	38	80	15	133	50.990	410	637.38	383.40	124.37	3.08	2.10	79
Average....	55.50	70.50	16.25	142.25	53.553	494.50	759.62	376.47	108.30	3.48	1.27	81
INFERTILE SOIL WITH MANURE												
13	134	189	34	357	106.550	851	563.76	298.44	125.21	2.38	1.41	86
16	141	172	34	347	107.600	882	625.58	310.09	122.00	2.54	1.22	92
41	146	233	29	408	113.830	865	488.50	279.00	131.60	2.12	1.59	104
44	149	167	29	345	102.400	826	613.18	296.80	123.99	2.39	1.12	94
Average....	142.50	190.25	31.50	364.25	107.595	856.00	565.55	295.39	125.70	2.35	1.34	94
INTERMEDIATE SOIL												
12	164	139	33	336	107.300	796	772.00	319.34	134.80	2.37	.85	91
17	106	197	27	330	81.350	558	412.98	246.51	145.78	1.69	1.86	86
40	136	159	32	327	96.270	968	605.48	294.40	99.45	2.96	1.17	81
45	136	161	28	325	96.760	750	601.00	297.72	129.01	2.31	1.18	110
Average....	135.50	164.00	30.00	329.50	95.420	768.00	581.83	289.59	124.24	2.33	1.21	92

TABLE 62 CONTINUED.—*Summary of data secured from potometers containing soils of six degrees of fertility. 1911.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Grams* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
INTERMEDIATE SOIL WITH MANURE												
11	160	250	35	445	121.090	769	484.36	272.11	157.46	1.73	1.56	82
18	217	222	40	479	139.370	1,058	627.80	290.96	131.73	2.21	1.02	99
39	161	247	32	440	120.860	813	489.31	274.70	148.66	1.85	1.53	100
46	164	194	27	385	97.890	848	504.59	254.26	115.43	2.20	1.18	106
Average....	175.50	228.25	33.50	437.25	119.803	872.00	524.88	273.99	137.39	1.99	1.30	97
FERTILE SOIL												
10	157	264	42	463	113.920	956	431.51	246.05	119.16	2.07	1.68	84
19	167	188	35	390	111.160	902	591.27	285.03	123.24	2.31	1.13	95
38	138	224	29	391	98.520	802	439.80	251.97	122.84	2.05	1.62	91
47	162	228	35	425	113.150	895	496.30	266.23	126.42	2.11	1.41	95
Average....	156.00	226.00	35.25	417.25	109.188	888.75	483.13	261.68	122.86	2.13	1.45	91
FERTILE SOIL WITH MANURE												
20	171	214	33	418	118.130	802	552.01	282.60	147.29	1.92	1.25	81
37	169	314	36	519	116.960	918	372.50	225.36	127.40	1.77	1.86	102
48	154	221	30	405	100.810	932	456.15	248.91	108.16	2.30	1.44	90
Average....	164.67	249.67	33.00	447.33	111.967	884.00	448.46	250.30	126.66	1.98	1.52	91

TABLE 63.—*Summary of results secured during two years from potometers containing six degrees of soil fertility. 1911 and 1914. (Hogue's Yellow Dent corn used in 1911 and Pride of the North 1914.)*[1]

Yr.	Moisture-free manure added	No. of potos. averaged	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
			Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Pounds* (2)	(3)	*Grams* (4)	*Grams* (5)	*Grams* (6)	*Grams* (7)	*Kilograms* (8)	*Sq. in.* (9)	*Grams* (10)	*Grams* (11)	*Grams* (12)	*Sq. in.* (13)	(14)	*Inches* (15)
INFERTILE SOIL														
1911	0	4	61	37	15	113	61.96	477	1,686	550	130	4.2	.60	68
1914	0	4	56	71	16	142	53.55	495	760	376	108	3.5	1.30	81
Av..	0	8	59	54	15.5	128	57.76	486	1,223	463	119	3.9	.95	75
INFERTILE SOIL WITH MANURE														
1911	2.4	4	150	194	32	376	131.65	980	679	350	134	2.6	1.30	92
1914	1.75	4	143	190	32	364	107.60	856	566	295	126	2.4	1.30	94
Av..	2.1	8	147	192	32	370	119.63	918	623	323	130	2.5	1.30	93
INTERMEDIATE SOIL														
1911	0	4	89	77	18	184	88.31	637	1,140	479	139	3.5	.87	81
1914	0	4	136	164	30	330	95.42	768	582	290	124	2.3	1.20	92
Av..	0	8	113	121	24	257	91.87	702	861	384	132	2.9	1.04	87
INTERMEDIATE SOIL WITH MANURE														
1911	2.4	4	172	210	32	414	141.08	890	672	341	159	2.2	1.20	92
1914	1.75	4	176	228	34	437	119.80	872	525	274	137	2.0	1.30	97
Av..	2.1	8	174	219	33	426	130.44	881	599	308	148	2.1	1.25	95
FERTILE SOIL														
1911	0	4	111	135	24	270	105.84	688	785	392	154	2.6	1.20	83
1914	0	4	156	226	35	417	109.19	889	483	262	123	2.1	1.50	91
Av..	0	8	134	181	30	344	107.51	789	634	327	139	2.4	1.35	87
FERTILE SOIL WITH MANURE														
1911	2.4	3	194	242	37	473	163.69	993	677	346	165	2.1	1.30	95
1914	1.75	3	165	250	33	447	111.97	884	448	250	127	2.0	1.50	91
Av..	2.1	6	180	246	35	460	137.83	939	563	298	146	2.0	1.40	93

[1] Compiled from Tables Nos. 61 and 62.
For a discussion of method used in compiling averages for two or more years, see page 42.

TABLE 64.—*Showing in per cent the effect of applying manure to potometers of different degrees of soil fertility. The results with manure are here expressed in per cent of the results without manure. (Average 1911 and 1914.)*[1]

Yr.	Moisture-free manure added	No. of potos. averaged	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
			Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Pounds* (2)	(3)	*Per cent* (4)	*Per cent* (5)	*Per cent* (6)	*Per cent* (7)	*Per cent* (8)	*Per cent* (9)	*Per cent* (10)	*Per cent* (11)	*Per cent* (12)	*Per cent* (13)	*Per cent* (14)	*Per cent* (15)
INFERTILE SOIL WITH MANURE														
1911	2.4	4	245.9	524.3	213.3	332.7	212.5	205.4	40.3	63.6	103.0	61.9	216.7	135.3
1914	1.75	4	255.4	267.6	200.0	256.3	200.9	172.9	74.5	78.5	116.7	68.6	100.0	116.1
Av..	2.1	8	250.7	396.0	206.7	294.5	206.7	189.2	57.4	71.1	109.9	65.3	158.4	125.7
INTERMEDIATE SOIL WITH MANURE														
1911	2.4	4	193.3	272.7	177.8	225.0	159.7	139.7	58.9	71.2	114.4	62.9	137.9	113.6
1914	1.75	4	129.4	139.0	113.3	132.4	125.5	113.5	90.2	94.5	110.5	87.0	108.3	105.4
Av..	2.1	8	161.4	205.9	145.6	178.7	142.6	126.6	74.6	82.9	112.5	74.9	123.1	109.5
FERTILE SOIL WITH MANURE														
1911	2.4	3	174.8	179.3	154.2	175.2	154.7	144.3	86.2	88.3	107.1	80.8	108.3	114.4
1914	1.75	3	105.8	110.6	94.3	107.2	102.6	99.4	92.8	95.4	103.3	95.2	100.0	100.0
Av..	2.1	6	140.3	145.0	124.3	141.2	128.7	121.9	89.5	91.9	105.2	88.0	104.2	107.2

[1] Calculated from data in Table 63.

DISCUSSION OF RESULTS.

The results of the experiments during 1911 and 1914 have been summarized in Tables 63 and 64. The reader is referred to these two summary tables for a full and concise statement of results. The average production for the two years shows that three very distinct degrees of natural fertility existed.

Without fertilizer, the average yields of dry matter from the infertile, intermediate, and fertile soils were 128, 257, and 344 grams per plant, while the ear weights were 54, 121, and 181 grams per plant. The respective amounts of water transpired per plant were 57.76, 91.87, and 107.51 kilograms. The water transpired per gram dry weight of ear was 1,223, 861, and 634 grams according to fertility, while the water requirements per gram total dry matter were 463, 384, and 327 grams. The differences between the water losses per square inch of leaf-area, which were 119, 132, and 139 grams, are not very significant. The comparatively low ratio for the infertile soil can be explained at least partially by the smaller height of the plants and also by a somewhat slower vegetative development.

Table 64 shows the effect in percentage of applying manure to the three natural soils differing in fertility. The average for the unfertilized potometers is in each instance used as a basis and is regarded as 100 per cent. The application of manure increased the yield of dry matter per plant in the order of infertile, intermediate, and fertile soil, 194.5, 78.7, and 41.2 per cent. The weight of ears was increased 296, 105.9, and 45 per cent. The total water transpired per plant was increased 106.7, 42.6, and 28.7 per cent. Again in the order of infertile, intermediate, and fertile soil the manure reduced the water requirement per gram dry weight of ear 42.6, 25.4, and 10.5 per cent. The water requirement per gram total dry matter was reduced 28.9, 17.1, and 8.1 per cent. The water used per square inch leaf-area was increased by the manure 9.9, 12.5, and 5.2 per cent. The more infertile the soil, the greater was the effect of manure in increasing the dry matter per unit leaf-area, and in increasing the relative ear development in proportion to stalk. A brief summary of the results is given in Table 65.

TABLE 65.—*Summary showing the relative dry matter and water requirements of corn on the different soil types during two years—1911 and 1914.*[1]

Character of soil	Dry matter per plant (grams)		Total water transpired per plant.[1] (kilograms)		Water used per gram of dry matter (grams)	
	Unmanured	Manured	Unmanured	Manured	Unmanured	Manured
	(1)	(2)	(3)	(4)	(5)	(6)
YEAR 1911						
Infertile	113	376	61.96	131.65	550	350
Intermediate	184	414	88.31	141.08	479	341
Fertile	270	473	105.84	163.69	392	346
YEAR 1914						
Infertile	142	364	53.55	107.60	376	295
Intermediate	330	437	95.42	119.80	290	274
Fertile	417	447	109.19	111.97	262	250
AVERAGE FOR 1911 AND 1914						
Infertile	128	370	57.76	119.63	463	323
Intermediate	257	426	91.87	130.44	384	308
Fertile	344	460	107.51	137.83	327	298

[1] Compiled from Table 63.

For a discussion of method used in compiling averages for two or more years, see page 42.

It is very evident that an application of manure to the infertile soil reduced the water requirement per unit dry matter in a very marked manner. The effect upon a fertile soil was, however, much less marked. These results would at first thought appear to confirm the prevalent belief that increasing the fertility of the soil reduces the amount of water transpired by the crop. But when we look at the column showing the total amount of water used per plant, we see that an actually much greater amount of water is used rather than a reduced amount of water. This is due to an increased development of the plant and greater transpiring surface. The reduction in the amount of water transpired per gram dry matter is due not to a reduction in the transpiration rate from the plant, but rather to a much more vigorous and constant growth of the plant. The situation may, in a general way, be stated as follows:

In a fertile soil the plant continues to increase in dry matter in a thrifty manner all of the time that it is transpiring water. In an infertile soil, on the contrary, the plant continues to transpire water, but the increase in dry matter is greatly retarded because of malnutrition.

These apparently contradictory and yet very logical water relationships may be clearly brought out in Charts XIX and XX.

There is a rather prevalent popular theory that the absorption of food materials from the soil is dependent upon the transpiration rate; that in an infertile soil containing a weak nutrient solution, the crop must transpire at a relatively much more rapid rate in order to obtain the necessary amount of nutrients; that the plant exercises control over this transpiration rate and thereby can control the amount of nutrients absorbed; and that in a fertile soil containing a strong nutrient solution the necessary amount of nutrient materials may be absorbed with a relatively small amount of water, thus making it possible for the plant to thrive on a much smaller amount of water. Indications are, however, that the transpiration rate is independent of the strength of the soil solution, and that a more fertile soil does not lower the total amount of water necessary for the plant but rather increases the production thru increased vigor of growth, and thereby coincidentally reduces the amount of water used per unit dry matter.

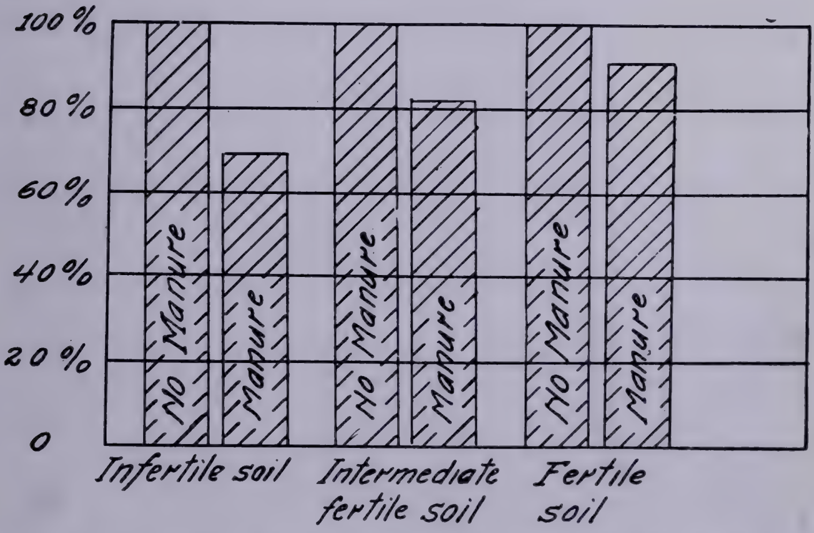

Chart XIX.—Effect of manure on the water requirement per unit of dry matter with corn. Average of 1911 and 1914. Graph from Table 65.

The application of fertilizer increases the relative yield more proportionally than the total water transpired. This results in greater efficiency of the plant and a consequent greater production in proportion to the water consumed. Popularly this is said to reduce the water requirement, tho in fact it is not a function of the transpiration at all but merely a coincidence.

The ease with which evaporation takes place from the plant will not be materially reduced or increased whether the solution absorbed is dense or not. As Livingston (1911, p. 161) has stated, "A solution of the strength of the highest concentration

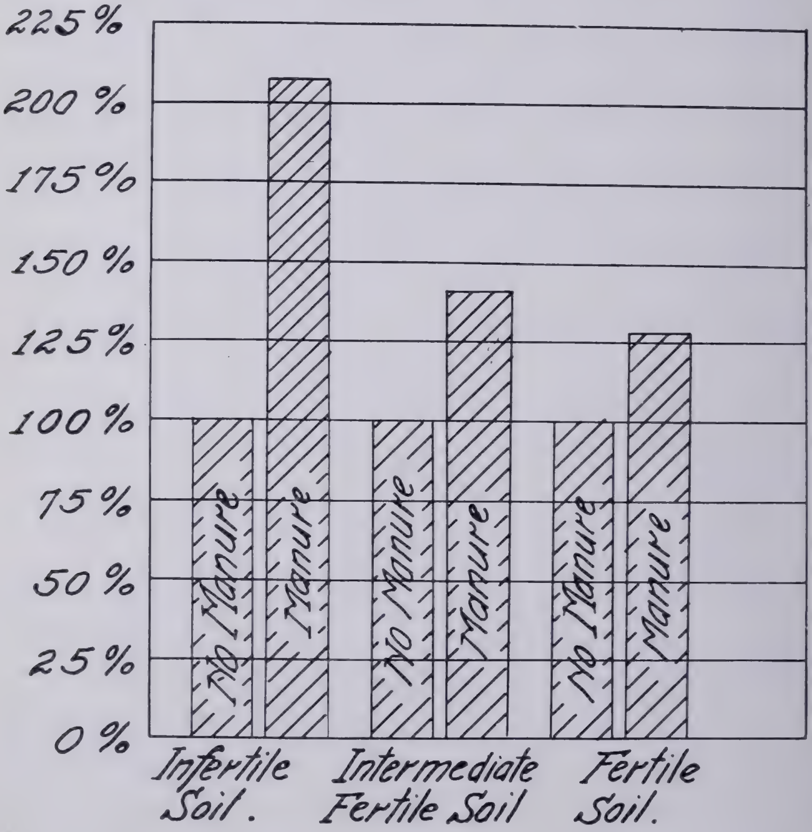

Chart XX.—Effect of manure on the total water transpired per plant with corn. Average, 1911 and 1914. Graph from Table 65.

found by Fitting (1911) in the foliar cell sap of desert plants (something over one hundred atmospheres of osmotic pressure), possesses a vapor tension less than 10 per cent below that of pure water and should therefore evaporate more than 90 per cent as rapidly."

EFFECT OF PROLONGED CONFINEMENT IN CANS OF SOILS DIFFERING IN FERTILITY.

The plan of the experiment recorded in Table 66 has been discussed on page 143. Attention has been called to the fact that after the first year the plants lacked their normal thrift in these soils. They assumed a yellowish color and made poor growth as tho the soil had greatly deteriorated in available fertility. This effect is attributed to a lack of aeration under the conditions prevailing. The low productivity cannot in all probability be assigned to a toxic effect from continuous cropping to corn, for the reason that four years of continuous corn cropping under field conditions on similar soil does not appear to be similarly injurious.

TABLE 66.—*Summary showing plant growth and water requirements of corn in six degrees of soil fertility during four consecutive years, 1911 to 1914. The potometers were filled in 1911 and the same soil remained in them undisturbed thruout the period.*[1]

Year	No. of potometers averaged	Dry matter		Total water transpired	Transpiration per gram	
		Ear	Total		Dry weight of ear	Total dry matter
(1)	(2)	*Grams* (3)	*Grams* (4)	*Kilograms* (5)	*Grams* (6)	*Grams* (7)
			INFERTILE SOIL			
1911....	4	36.74	112.75	61.961	1,686.47	549.50
1912....	4	12.83	55.36	29.215	2,277.08	527.73
1913....	4	9.67	87.33	62.362	6,449.02	714.10
1914....	4	16.00	76.25	37.150	2,321.88	487.21
Average	16	18.81	82.92	47.67	3,183.61	569.64
			INFERTILE SOIL WITH MANURE			
1911...	4	193.99	375.82	131.653	678.66	350.30
1912...	4	114.63	188.21	47.432	413.78	252.02
1913...	4	81.50	215.25	109.815	1,347.42	510.17
1914...	4	53.50	163.25	61.890	1,156.82	379.11
Average	16	110.91	235.63	87.698	899.17	372.90

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[1] See footnote, p. 158.

TABLE 66 CONTINUED.—*Summary showing plant growth and water requirements of corn in six degrees of soil fertility during four consecutive years, 1911 to 1914. The potometers were filled in 1911 and the same soil remained in them undisturbed thruout the period.*[1]

Year	No. of potometers averaged	Dry matter		Total water transpired	Transpiration per gram	
		Ear	Total		Dry weight of ear	Total dry matter
(1)	(2)	*Grams* (3)	*Grams* (4)	*Kilograms* (5)	*Grams* (6)	*Grams* (7)
INTERMEDIATE SOIL						
1911	4	77.48	184.39	88.306	1,139.73	478.90
1912	4	34.88	78.99	35.480	1,017.21	449.16
1913	4	25.67	114.67	65.430	2,548.89	570.59
1914	4	20.50	103.50	49.520	2,415.61	478.45
Average	16	39.63	120.93	59.68	1,780.36	494.28
INTERMEDIATE SOIL WITH MANURE						
1911	4	209.79	413.63	141.079	672.48	341.10
1912	4	101.48	182.26	50.269	495.36	275.81
1913	4	77.00	218.75	108.773	1,412.69	497.25
1914	4	75.75	215.75	74.080	977.95	343.35
Average	16	116.01	257.60	93.55	889.62	364.38
FERTILE SOIL						
1911	4	134.77	269.85	105.840	785.34	392.22
1912	4	92.70	167.14	44.235	477.18	264.66
1913	4	85.50	224.25	122.269	1,429.94	545.24
1914	4	57.00	167.00	63.710	1,117.72	381.50
Average	16	92.49	207.06	84.01	952.55	395.91
FERTILE SOIL WITH MANURE						
1911	3	241.88	472.55	163.685	676.72	346.40
1912	4	132.75	241.58	56.767	427.62	234.98
1913	4	122.25	308.25	136.986	1,120.54	444.40
1914	4	137.00	288.50	89.320	651.97	309.60
Average	15	158.47	327.72	111.69	719.21	333.85

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[1] With the exception of 1911, the plants in these tests were abnormal. The data in Summary Table 60 should be relied upon to illustrate the principles concerning the relation of soil fertility to water requirement.

For a discussion of method used in compiling averages for two or more years, see page 42.

Aside from a lack of thrift during the last three years, the reduced yield might be partially explained by the fact that a smaller variety (Pride of the North) was grown than the Hogue's Yellow Dent variety of the first year. A comparison of these two corns was made in the variety test of 1914. The Hogue's Yellow Dent corn produced 25 per cent greater dry matter. However, in this fertility experiment, the average yield of dry matter for the six degrees of fertility was 304.9 grams in 1911 and only 169.0 grams in 1914. It might be stated in this connection that in all the experiments reported in this bulletin, with this one exception, the potometers were filled with new soil every year. In spite of the abnormal condition of the plants in this experiment, the data show a very marked residual effect of manure on production for four years. The cause of this deterioration of soil productivity from prolonged confinement in cans will be further investigated.

INFLUENCE OF ACCLIMATIZATION, VARIETY, AND KIND OF CROP UPON THE TRANSPIRATION RELATIONSHIPS.[1]

In 1914 a comparative study was made of the use of water by corn differing in acclimatization, growth habits, erectness of leaves, and alleged drouth resistance. Sorghums and wild sunflowers were also compared with corn. The ears harvested from the different corn varieties are shown in Figure 21.

The plants were grown singly in potometers 16 by 36 inches in size, containing 248 pounds of fertile, moisture-free surface soil, and having an application of 1.75 pounds of well-rotted moisture-free sheep manure mixed in with the upper 10 inches of soil. A constant and uniform amount of moisture was available to all plants. The results are given in detail in Table 67 and are summarized in Table 68.

ACCLIMATIZATION.[2]

Two varieties of corn (Rocky Mountain Dent and Wood's White Dent), acclimatized to the humid soil and climate of New York, were compared with two varieties (Calico from North Platte, Nebr., and Martens' White Dent from Chadron, Nebr.)

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[1] References concerning the relation of transpiration to kind of crop and variety: Briggs and Shantz (1913, 1914), Hellriegel (1883), King (1892, 1893, 1894, and 1895), Lawes (1850), Leather (1910, 1911), Seelhorst (1906, 1908), Sorauer (1883), Thom (1913), Thom and Holtz (1914), Widtsoe (1909), Widtsoe and Merrill (1902), Willard and Humbert (1913), and Wollny (1877).

[2] The Rocky Mountain Dent, Wood's White Dent, and Martens' White Dent corn were secured from C. P. Hartley of the United States Department of Agriculture. The Calico corn was obtained from W. P. Snyder, Superintendent of the North Platte Experimental Substation, North Platte, Nebr.

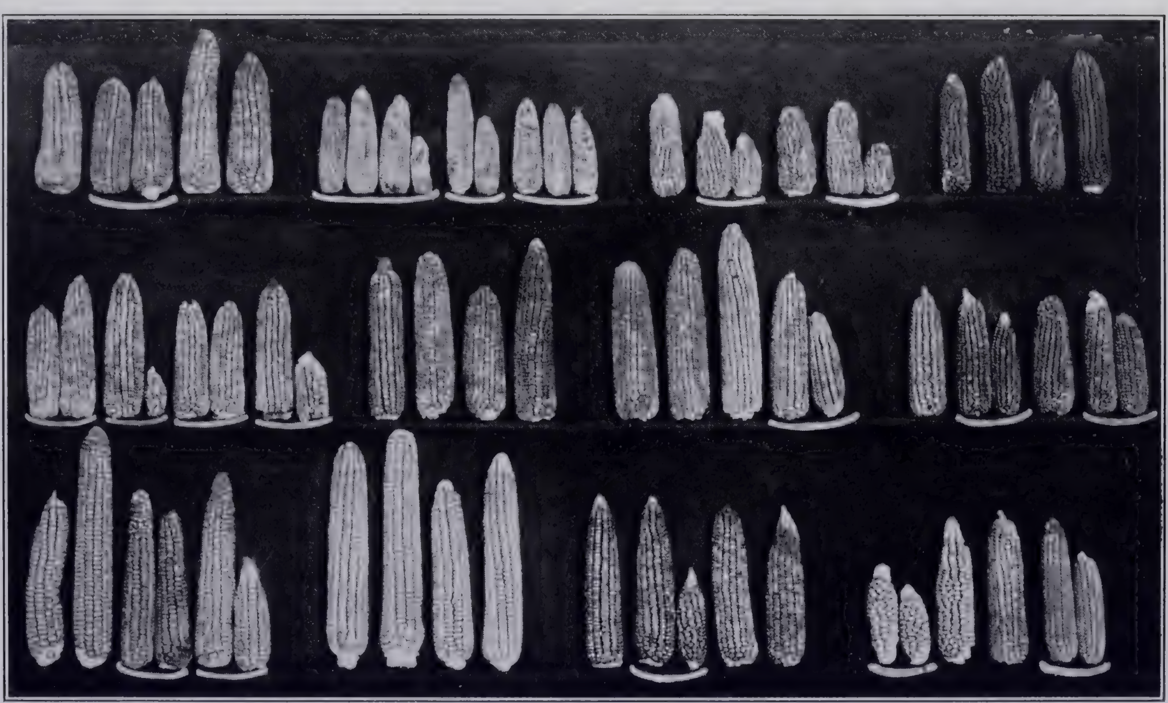

Fig. 21.—Ears produced in potometers in the corn variety and acclimatization test. 1914. Reading from left to right: 1, Sherrod's Kansas Dent corn; 2, Chinese corn (3 plants); 3, Roberts' hybrid between Sherrod's Kansas Dent corn, Chinese corn, and Esperanza corn; 4, Emerson's Liguleless-leaf corn; 5, Pride of the North from Lincoln, Nebr.; 6, University No. 3 from Lincoln, Nebr.; 7, Hogue's Yellow Dent from Lincoln, Nebr.; 8, Emerson's Normal Dent corn (for comparison with No. 4); 9, Rocky Mountain Dent corn from New York; 10, Wood's White Dent from New York; 11, Calico from North Platte, Nebr.; 12, Martens' White Dent from Chadron, Nebr. See Table 64.

TABLE 67.—*Relative water requirements of crops and varieties. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
ROCKY MOUNTAIN DENT CORN FROM NEW YORK												
1	124	132	21	277	77.410	670	586.40	279.45	115.54	2.42	1.06	84
58	167	267	48	482	119.550	1,000	447.78	248.02	119.55	2.07	1.60	93
59	163	289	37	489	122.710	934	424.60	250.95	131.39	1.91	1.77	91
116	148	224	28	400	121.900	761	544.21	304.78	160.19	1.90	1.51	89
Average....	150.50	228.00	33.50	412	110.393	841.25	484.20	267.94	131.22	2.04	1.52	89
CALICO CORN FROM NORTH PLATTE, NEBRASKA												
2	216	227	45	488	130.220	1,084	573.68	266.84	120.13	2.22	1.05	92
57	193	305	67	565	127.540	1,168	418.15	225.73	109.20	2.07	1.58	97
60	142	214	35	391	104.780	865	489.61	268.00	121.13	2.21	1.51	90
115	132	129	44	305	92.730	1,035	718.84	304.03	89.59	3.39	.98	92
Average....	170.75	218.75	47.75	437.25	113.818	1,038.00	520.31	260.30	109.65	2.37	1.28	93
WOOD'S WHITE DENT CORN FROM NEW YORK												
3	229	244	55	528	143.480	1,221	588.00	271.72	117.50	2.31	1.07	110
56	185	287	45	517	114.960	1,178	400.60	222.35	97.59	2.28	1.55	108
61	197	247	47	491	125.000	978	506.08	254.60	127.82	1.99	1.25	106
114	174	254	41	469	117.880	1,034	464.11	251.35	114.10	2.20	1.46	104
Average....	196.25	258.00	47.00	501.25	125.330	1,102.75	485.78	250.03	113.65	2.20	1.31	107
MARTENS' WHITE DENT CORN FROM CHADRON, NEBRASKA												
4	153	104	32	289	93.970	764	903.60	325.15	123.00	2.64	.68	97
55	131	159	31	321	85.240	647	536.09	265.54	131.74	2.02	1.21	79
62	131	200	38	369	78.450	730	392.25	212.59	107.46	1.98	1.53	78
113	118	201	34	353	77.920	892	387.66	220.74	87.35	2.53	1.70	84
Average....	133.33	166.00	33.75	333.00	83.895	758.25	505.39	251.94	110.64	2.28	1.25	84

TABLE 67 CONTINUED.—*Relative water requirements of crops and varieties. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
						PRIDE OF THE NORTH CORN						
5	177	273	47	497	111.610	912	408.81	224.56	122.38	1.84	1.54	106
54	159	216	30	405	97.790	777	452.73	241.45	125.85	1.92	1.36	92
63	129	259	52	440	96.730	722	373.46	219.82	133.96	1.64	2.01	98
112	146	262	36	444	104.890	842	400.37	236.24	124.57	1.90	1.79	96
Average....	152.75	252.50	41.25	446.50	102.755	813.25	406.95	230.13	128.35	1.82	1.65	98
						UNIVERSITY NO. 3 DENT CORN						
6	191	203	31	425	126.750	831	624.40	298.25	152.52	1.96	1.06	93
53	221	235	35	491	134.090	1,036	570.60	273.11	129.43	2.11	1.06	92
64	242	212	49	503	149.910	1,144	707.14	298.03	131.04	2.27	.88	98
111	167	257	51	475	129.340	1,088	503.26	272.30	118.86	2.29	1.54	95
Average....	205.25	226.75	41.50	473.50	135.020	1,024.75	595.46	285.15	131.76	2.16	1.10	94
						HOGUE'S YELLOW DENT CORN						
7	313	276	58	647	181.590	1,478	657.93	280.66	122.85	2.28	.88	126
52	205	320	48	573	154.480	1,315	482.75	269.60	117.48	2.29	1.56	115
65	225	352	51	628	181.610	1,190	515.94	289.20	152.60	1.90	1.56	110
110	158	273	40	471	119.670	928	438.35	254.10	128.96	1.97	1.73	94
20	219	284	50	553	140.380	1,324	494.29	253.89	106.03	2.39	1.30	118
39	227	329	52	608	165.550	1,635	503.19	272.30	101.28	2.69	1.45	121
78	193	287	52	532	137.570	1,454	479.34	258.60	94.62	2.73	1.49	120
97	226	179	44	449	132.990	1,248	742.96	296.20	106.58	2.78	.79	110
Average....	220.75	287.5	49.4	557.63	151.730	1,321.5	527.76	272.12	114.82	2.37	1.30	114
						EMERSON'S LIGULELESS DENT CORN						
8	112	118	27	257	85.880	780	727.80	334.15	110.10	3.03	1.05	97
51	136	160	29	325	89.750	739	560.94	276.14	121.44	2.27	1.18	100
66	132	160	33	325	92.770	740	579.81	285.44	125.35	2.28	1.21	79
109	132	182	32	346	102.310	812	562.14	295.69	126.00	2.35	1.38	114
Average....	128.00	155.00	30.25	313.25	92.678	767.75	597.92	295.86	120.71	2.45	1.21	97

TABLE 67 CONTINUED.—*Relative water requirements of crops and varieties. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area	Transpiration per			Leaf-area per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear	gram total dry matter	sq. in. leaf-area			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
EMERSON'S NORMAL DENT CORN												
9	120	140	27	287	76.330	621	545.22	265.96	122.92	2.16	1.17	77
50	123	216	34	373	79.580	826	368.43	213.34	96.35	2.21	1.76	92
67	110	160	33	303	81.200	603	507.50	267.99	134.65	1.99	1.45	72
108	124	183	39	346	87.560	790	478.47	253.06	110.84	2.28	1.48	100
Average....	119.25	174.75	33.25	327.25	81.168	710	464.48	248.03	114.32	2.17	1.47	85
ROBERTS' KANSAS DENT × CHINESE × ESPERANZA HYBRID CORN												
11	138	104	32	274	67.470	769	648.79	246.23	87.74	2.81	.75	72
48	177	120	35	332	83.060	910	692.14	250.16	91.28	2.74	.68	96
69	196	108	49	353	86.980	1,023	805.38	246.40	85.03	2.90	.55	87
106	199	134	45	378	102.670	1,091	766.19	271.61	94.11	2.89	.67	85
Average....	177.50	116.50	40.25	334.25	85.045	948.25	730.00	254.44	89.69	2.84	.66	85
SHERROD'S KANSAS DENT CORN												
10	245	161	51	457	132.640	1,051	823.91	290.28	126.20	2.30	.66	91
49	202	353	50	605	148.020	1,057	419.33	244.66	140.03	1.75	1.75	96
68	238	204	44	486	131.000	918	642.20	269.56	142.70	1.89	.86	102
107	105	228	35	368	81.110	670	355.75	220.41	121.06	1.82	2.17	65
Average....	197.50	236.50	45.00	479.00	123.193	924.00	520.90	257.19	133.32	1.93	1.20	88
CHINESE CORN												
12	198	257	60	515	127.730	1,381	497.00	248.00	92.49	2.68	1.30	73
47	236	131	41	408	106.240	1,172	811.00	260.40	90.66	2.87	.56	80
105	185	211	57	453	108.700	1,087	515.20	239.98	100.00	2.40	1.14	76
Average....	206.33	199.67	52.67	458.67	114.220	1,213.33	572.10	249.02	94.14	2.65	.97	76

TABLE 67 CONTINUED.—*Relative water requirements of crops and varieties. 1914.*

Potometer No.	Dry matter				Total water transpired	Total leaf-area[1]	Transpiration per			Leaf-area[1] per gram dry matter	Ratio of wt. of ear to wt. of stalk	Height of stalk
	Stalk	Ear	Leaves	Total			gram dry wt. of ear[1]	gram total dry matter	sq. in. leaf-area[1]			
(1)	*Grams* (2)	*Grams* (3)	*Grams* (4)	*Grams* (5)	*Kilograms* (6)	*Sq. in.* (7)	*Grams* (8)	*Grams* (9)	*Grams* (10)	*Sq. in.* (11)	(12)	*Inches* (13)
MILO (SORGHUM)												
14	241	218	49	508	137.810	....	632.16	271.28	....	....	.90	92
45	236	275	49	560	141.590	....	514.86	252.84	....	....	1.17	102
72	311	351	70	732	170.570	....	485.95	233.02	....	....	1.13	86
103	208	298	42	548	153.820	....	516.17	280.69	....	....	1.43	81
Average....	249.00	285.50	52.50	587.00	150.948	....	528.71	257.15	....	....	1.15	90
BLACK AMBER SORGHUM												
16	67	75	9	151	43.800	....	584.00	290.07	....	....	1.12	60
43	51	84	9	144	57.640	....	567.14	330.82	....	....	1.65	54
74	118	74	14	206	57.190	....	772.84	277.62	....	....	.63	77
101	117	76	16	209	69.300	....	911.84	331.58	....	....	.65	71
Average....	88.25	77.25	12.00	177.50	54.483	....	705.28	306.95	....	....	.88	66
WILD SUNFLOWER												
17	672	221	131	1,039	503.240	....	2,277.10	474.35	....	....	.33	162
42	552	148	126	826	534.660	....	3,612.57	647.29	....	....	.27	149
75	548	126	63	737	475.620	....	3,774.76	645.35	....	....	.23	117
100	548	175	126	849	514.330	....	2,939.03	605.81	....	....	.32	99
Average....	580.00	167.50	111.50	862.75	506.963	....	3,026.64	587.61	....	....	.29	132

[1] Leaf-area measurements were not made for the sorghums because the development of branches caused a continual change in the leaf-area.

TABLE 68.—*Effect of variety, adaptation, and kind of crop on the water requirement. 1914.*

Variety and source of seed	No. of potometers averaged	Dry wt. of ear	Total dry wt. of plant	Total water transpired	Water used per gr. dry wt. of ear	Water used per gr. total dry wt.	Average date ripe
		Grams	*Grams*	*Kilos.*	*Grams*	*Grams*	
	(1)	(2)	(3)	(4)	(4)	(6)	(7)
Rocky Mountain Dent corn from New York...	4	228	412	110.4	484	268	Aug. 24
Calico corn from North Platte, Nebr..........	4	219	437	113.8	520	260	" 27
Wood's White Dent corn from New York......	4	258	501	125.3	486	250	" 24
Martens' White Dent corn from Chadron, Nebr.	4	166	333	83.9	505	252	" 24
Pride of the North corn from Lincoln, Nebr....	4	252	446	102.8	407	230	" 24
University No. 3 corn from Lincoln, Nebr......	4	227	473	135.0	595	285	Sept. 1
Hogue's Yellow Dent corn from Lincoln, Nebr..	8	287	558	151.7	528	272	" 2
Emerson's liguleless dent corn from Lincoln, Nebr.	4	155	313	92.7	598	296	Aug. 27
Emerson's normal dent corn from Lincoln, Nebr..	4	175	327	81.2	464	248	" 23
Roberts' Kansas Dent × Esperanza × Chinese Hybrid corn..........................	4	116	334	85.0	730	254	Sept. 3
Sherrod's Kansas Dent corn from Kansas....	4	236	479	123.2	521	257	Aug. 29
Chinese corn from Kansas..................	3	200	459	114.2	572	249	Sept. 4
Milo (sorghum)..........................	4	285	587	150.9	529	257	Oct. 1
Black Amber sorghum......................	4	77	177	54.5	705	307	Sept. 5
Wild sunflower (*Helianthus annuus*)..........	4	167	863	507.0	3,027	588	Oct. 1

acclimatized to the relatively dry soil and atmosphere of western Nebraska. These varieties had been grown for many years in their respective localities. Very fortunately the average date of ripening was practically the same for all four varieties, so that no effect of difference in length of growing season need be considered. The yield and water requirement may be summarized as follows:

Description	Dry matter	Water requirement
	Grams	*Grams*
Rocky Mountain Dent from New York	412	268
Wood's White Dent from New York	501	250
Average	456	259
Calico from western Nebraska	437	260
Martens' White Dent from western Nebraska	333	252
Average	385	256

It would appear that the plants have developed no characteristics as a result of acclimatization which would cause them to differ in their water requirement.

DIFFERENCE IN GROWTH HABITS.

The object of this test was to compare early, medium, and late varieties, which might also be described as small, medium, and large. Three varieties grown in the vicinity of Lincoln, Nebr., were selected, namely, Pride of the North, University No. 3, and Hogue's Yellow Dent. The varieties did not differ as much in their growth in the potometers as had been expected. The results follow:

Description	Dry matter	Water requirement	Date ripe	Height
	Grams	*Grams*		*Inches*
Pride of the North	446	230	Aug. 24	94
University No. 3	473	285	Sept. 1	98
Hogue's Yellow Dent	558	272	Sept. 2	114

The data suggest that the Pride of the North corn used in this test was very efficient. The test will be repeated for a number of years to confirm the results. With Pride of the North corn, the low water requirement per unit dry matter was apparently due to the unusually good development of ears. Based on leaf-area the water requirement was not below normal.

ERECTNESS OF LEAVES.

Two related selections of corn differing in that the leaves of one of them has no ligules were secured from R. A. Emerson and compared as to their relative water requirements. This liguleless character of the leaves causes them to stand somewhat more erect, and it had been suggested that such a condition may reduce the exposure to evaporation influences and thus reduce the water requirement. The results follow:

Description	Dry matter	Water requirement
	Grams	*Grams*
Corn with normal leaves	327	248
Corn with liguleless leaves	313	296

Contrary to expectations, the liguleless corn had a considerably higher water requirement. The test needs verification with a greater number of selections. It is possible that one of the above selections was more efficient aside from this matter of the position of the leaves.

SPECIAL DROUTH-RESISTANT CORN.

The feature of this test was a hybrid[1] by H. F. Roberts in which he attempted to introduce the accredited drouth resistance of Chinese corn and Esperanza (Mexican hairy corn) into a standard variety of Kansas corn known as Sherrod's Dent corn. The Chinese and Esperanza corn have been described by G. N. Collins and are accredited by him to have great drouth resistance. The seed of all but the Esperanza was secured from Mr. H. F. Roberts, while the Esperanza was grown from old seed obtained four years ago from Mr. G. N. Collins. A satisfactory growth was obtained from all except Esperanza. All the plants of this variety were badly infected with smut and failed to produce ears, and for this reason the results from them are not included in the tables. The yield and water requirement may be summarized as follows:

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[1] The pedigree number given this seed by Mr. Roberts is F^3H58—9 A B C

	Dry matter	Water requirement
	Grams	*Grams*
1. Roberts' Chinese-Esperanza—Kansas Dent hybrid.	334	254
2. Chinese corn	459	249
3. Sherrod's Kansas Dent corn	479	257

The hybrid is evidently much less productive than the original Kansas Dent corn (Sherrod's) while the water requirement is practically the same. A striking observation concerning the hybrid was that the vegetative parts were much less pubescent than with either of the three varieties entering into the cross.

It is evident that if Chinese corn is especially drouth resistant it is so by virtue of other reasons than low water requirement.

SORGHUMS.

Milo and Black Amber sorghum were compared with our standard variety of Hogue's Yellow Dent corn.

Milo is a nonsaccharine grain sorghum, grown extensively in some regions for grain, while Black Amber is a saccharine sorghum grown primarily for forage. Both are recognized as unusually drouth-resistant crops as compared with corn, and the object of this experiment was to determine whether such drouth resistance may be due to a lower water requirement. The results follow:

	Dry matter	Water requirement
	Grams	*Grams*
Average for 11 corn varieties	418	258
Hogue's Yellow Dent corn	558	272
Milo	587	257
Black Amber sorghum	177	307

Compared with the average for 11 corn varieties, the milo and corn had practically the same water requirement per unit of dry matter, while sorghum exceeded the corn 16 per cent.

The milo used 5 per cent less water per unit dry matter than Hogue's Yellow Dent corn, while Black Amber sorghum used 13 per cent more.

These data suggest that other causes of drouth resistance in sorghums must be looked for than a relatively low water requirement. One cause doubtless is their ability to tide over a period

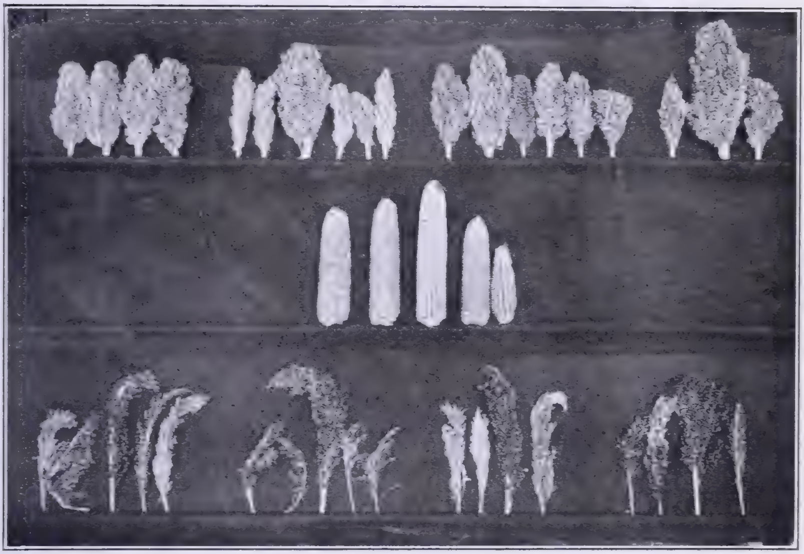

Fig. 22.—The product from four plants of milo, four plants of Hogue's Yellow Dent corn, and four plants of Black Amber sorghum. Grown in potometers. 1914.

of drouth in a relatively dormant state and resume growth when moisture comes, whereas corn does not so fully possess this quality.

WEEDS.

The common wild sunflower (*Helianthus annuus*) was compared with Hogue's Yellow Dent corn, which is a standard variety. The results may be summarized as follows:

	Dry matter	Water requirement	Total water used per plant
	Grams	*Grams*	*Kilograms*
Hogue's Yellow Dent corn	558	272	151.7
Wild sunflower	863	588	507.0

The sunflowers used more than three times as much water per plant as the corn, while the water used per unit dry matter was slightly more than double that of the corn. It is not unusual to see sunflower plants in cornfields as large as those grown in the potometers. Such a plant uses approximately as much water as a hill of corn with three plants.

RELATION OF ASH CONTENT TO TRANSPIRATION UNDER VARIOUS CONDITIONS OF GROWTH.[1]

There are two common theories relative to the relationship between the transpiration rate and the intake of soil solutes. According to one theory the amount of solute taken up by the plant from the soil solution is proportional to the amount of water transpired, and the amount of transpiration is in inverse ratio to the density of the solution. According to the second theory, the amount of solute taken in by the plant may be independent of the density of the solution and the amount of water transpired.

In order to secure information regarding these relationships, ash determinations[2] were made of a large number of the plants harvested in 1913 and 1914. Altho the ash left on incineration has not the composition of the inorganic compounds taken up by the plant from the soil, nevertheless it may serve as an index of the relative absorption of soil solutes. In these determinations every precaution was taken to insure the highest degree of accuracy. The whole plant was reduced to a fine powder, thoroly mixed, and sampled. The samples were ashed in a carefully regulated electric furnace, so that loss by volatilization was reduced to a minimum. In all cases duplicate determinations were made. The following tables contain data concerning the relation between transpiration and ash content, as affected by: (1) Atmospheric humidity, (2) seasonal climatic differences, (3) soil fertility, (4) soil moisture, (5) kind of crop and variety, and (6) limitation of the amount of soil thru the size of the potometer.

The complete plans and other detailed results with these plants have been given earlier in this bulletin, reference to the related data being given below each of these tables.

EFFECT OF CLIMATIC DIFFERENCES UPON RELATION OF TRANSPIRATION TO ASH CONTENT.

The plants grown in the dry and humid greenhouses in 1912 furnish excellent material to determine the effect upon the

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[1] References relative to transpiration and the intake of salts: Daszewski (1900), Fittbogen (1873), Hasselbring (1914a, 1914b), Il'enkov (1865), Lawes (1850), Preul (1908), Wilfarth and Wimmer (1902), and Wimmer (1908).

[2] The ash determinations were made under the direction of Dr. F. W. Upson, Station Chemist.

TABLE 69.—*Relation of ash content in the corn plant to the amount of transpiration as affected by a difference in atmospheric humidity. (Plants grown to silking stage in the dry and humid greenhouse 1912.)*[1]

	Small laboratory potometers pop corn			Potometers 16" x 36" Hogue's Yellow Dent corn		
	Dry greenhouse	Humid greenhouse	Ratio dry to humid	Dry greenhouse	Humid greenhouse	Ratio dry to humid
	(1)	(2)	(3)	(4)	(5)	(6)
Number of potometers averaged	10	9	....	5	5	....
Dry weight per plant (grams)	67.90	71.90	....	100.9	90.50	....
Ash content (per cent)	12.28	11.91	100:97	13.06	12.22	100:94
Total weight of ash (grams)	8.34	8.56	....	13.18	11.06	....
Total water transpired per plant (kilograms)	24.279	14.304	100:59	33.640	19.067	100:57
Water used per gram dry matter (grams)	357.30	198.80	100:56	333.40	210.70	100:63
Water transpired per gram ash content (kilograms)	2.91	1.67	100:57	2.55	1.72	100:67
Water transpired per square inch leaf-area	44.70	27.11	100:61	44.85	26.14	100:58
Water evaporated per square inch free water surface (grams)	125.50	66.20	100:53	151.39	80.03	100:53

[1] For further information concerning these plants see pp. 111 to 114.

relative intake of soil solutes of suppressing the transpiration rate thru increased atmospheric humidity.

Ash determinations were made of plants grown in comparable potometers in the field during 1913 and 1914 in the test for determining the seasonal effects upon transpiration. The 1913 and 1914 soil saturation tests also contained comparable plants during the two seasons 1913 and 1914, for which ash determinations have been made. The reader is referred to Tables 69, 70, and 71 for detailed data concerning these relationships, which are summarized in Table 72.

TABLE 70.—*Effect of difference in seasonal climatic conditions upon the relation between transpiration and the ash content of corn plants. 1913 and 1914.*[1]

	Year		
	1913	1914	Ratio 1913 to 1914
Dry weight per plant (grams)	372.00	443.00	....
Total weight of ash (grams)	23.68	22.29	....
Ash content (per cent)	6.37	5.03	100:79
Total water transpired per plant (kilos)	165.00	123.00	100:75
Water used per gram dry matter (grams)	445.00	277.00	100:62
Water transpired per gram ash content (kilograms)	6.97	5.52	100:79
Water transpired per sq. in. leaf-area (grams)	155.00	103.00	100:66
Water evaporated per sq. in. free water surface[2] (grams)	476.00	284.00	100:60

[1] Further data concerning these plants are reported in Tables 33 and 34, which contain five years' results showing the transpiration relationships in similarly treated potometers to seasonal climatic differences.

[2] Average for July and August.

By averaging the per cent ash ratios in the dry and humid greenhouses for the plants grown in both the large and small potometers during 1912, we secure an average ratio of 100:95.5. A similar ratio for the field potometers in 1913 and 1914 secured by averaging the ratios from the three different degrees of soil-moisture content and also from the plants reported in Table 70 gives a ratio of 100:93.5. The data of the three tables as summarized in Table 72 indicate that there may be considerable variation in per cent ash of the corn plant, but that as a general principle the per cent ash is slightly lower under climatic conditions having a low evaporation coefficient.

TABLE 71.—*Relation of ash content to transpiration from corn plants grown in three degrees of soil moisture content, as affected by the atmospheric evaporating power of two different seasons. 1913 and 1914.*[1]

	50 per cent saturation			70 per cent saturation			95 per cent saturation		
	1913	1914	Ratio 1913 to 1914	1913	1914	Ratio 1913 to 1914	1913	1914	Ratio 1913 to 1914
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Number of potometers averaged	7	4	....	8	4	....	8	4	....
Av. dry wt. per plant (grams)	233.86	512.00	....	407.63	560.50	....	372.00	488.25	....
Total ash content (grams)	14.66	27.57	....	21.92	32.27	....	23.46	31.35	....
Total water transpired per plant (kilograms)	85.764	142.371	....	156.542	170.757	....	159.294	154.051	....
Ash content (per cent)	6.27	5.38	100:86	5.39	5.76	100:107	6.31	6.42	100:102
Water transpired per gram dry matter (grams)	367.00	278.00	100:76	384.00	305.00	100:79	428.00	316.00	100:74
Water transpired per gram ash content (kilograms)	5.85	5.16	100:88	7.14	5.29	100:74	6.79	4.92	100:72
Water transpired per square inch leaf-area (grams)	110.00	101.00	100:92	165.00	119.00	100:72	172.00	110.00	100:64
Water evaporated per square inch free water surface (grams)[2]	476.00	284.00	100:60	476.00	284.00	100:60	476.00	284.00	100:60

[1] For detail information concerning this experiment see pages 127 to 142.

These data are taken from Tables 56, using only the potometers without manure for 1914, so as to make the data comparable during the two years.

[2] Average for July and August.

TABLE 72.—*Summary of ratios for dry and humid greenhouses, 1912, and for two years, 1913 and 1914.*

	Ratio of dry to humid greenhouse 1912[1]			Ratio of 1914 to 1913 field potometers[2]				
	Small potometers	Large potometers	Average	50 per cent saturation	70 per cent saturation	95 per cent saturation	Standard potometers[2]	Average
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ash content (per cent)	100:97	100:94	100:95.5	100:86	100:107	100:102	100:79	100:93.5
Water used per gram dry matter (grams)	100:56	100:63	100:59.5	100:76	100:79	100:74	100:62	100:73.0
Water transpired per gram ash content (kilograms)	100:57	100:67	100:62.0	100:88	100:74	100:72	100:79	100:78.0
Water transpired per square inch leaf-area (grams)	100:61	100:58	100:59.5	100:92	100:72	100:64	100:66	100:73.5
Water evaporated per square inch free water surface (grams)	100:53	100:53	100:53.0	100:60	100:60	100:60	100:60	100:60.0

[1] From Table 69.
[2] From Table 70 and 71.
[3] Potometers used in test for determining seasonal effects (Table 33).

Under comparable greenhouse conditions an increase in relative atmospheric humidity which lowered the evaporation rate from a free water surface 47 per cent reduced the amount of water transpired per gram ash content 38 per cent, and per gram dry matter 40.5 per cent.

In comparable potometers situated in the cornfield during two years (1913 and 1914), a difference in climatic factors, which lowered the evaporation rate from a free water surface 40 per cent during July and August, reduced the transpiration per gram ash content 22 per cent and per gram dry matter 27 per cent. (Table 72.)

EFFECT OF DIFFERENCES IN SOIL FERTILITY UPON RELATION OF TRANSPIRATION TO ASH CONTENT.

An ash determination was made for all the plants grown during the season of 1914 in the new fertility series and also for the plants grown during both 1913 and 1914 in the old fertility series which was commenced in 1911. A full description of the experiment with other tables and conclusions is given in pages 143 to 158.

It will be recalled (p. 145) that the plants reported in Table 73 were entirely normal according to the fertility of the soil, while those in Table 74 were not entirely normal due to soil deterioration from prolonged confinement in the potometers. As a result, the data in Table 73 are normal. The differences secured from the old fertility series according to the various soil types are so marked, however, that the data appear of value in corroborating the results in Table 73 and to help establish a general principle.

The results for the separate experiments have been averaged together in Table 75. In all three tests the amount of water transpired per gram ash content was reduced somewhat as the fertility of the soil was increased. It would probably be more accurate to say that the amount of solute per unit water taken in by the plant was increased as the fertility of the soil was increased. The denser soil solution did not, however, reduce the actual transpiration rate, for in fact the total amount of water transpired per plant increased consistently as the strength of the soil solution increased. This correlates rather closely with the relative amounts of water used per gram dry matter. The greater the availability of the soil solutes within the limits of these tests (1) the greater was the amount of solute taken in per unit water, (2) the greater was the dry matter produced, (3) the greater was the total amount of water transpired, (4) the greater was the total amount of solute taken into the plant, and (5) the smaller was the amount of water used per unit dry matter.

TABLE 73.—*Relation of ash content of Pride of the North corn plants to transpiration and fertility of soil.*[1] *(Potometers filled and started in 1914.) 1914.*

Description		Dry matter			Per cent ash			Total ash content	Total transpiration	Water transpired per gram total dry matter	Water transpired per gram ash content
Soil type	Moisture-free manure added	Grain	Stover[2]	Total	Grain	Stover	Total				
	Pounds	*Grams* (1)	*Grams* (2)	*Grams* (3)	*Per ct.* (4)	*Per ct.* (5)	*Per ct.* (6)	*Grams* (7)	*Kilos.* (8)	*Grams* (9)	*Kilograms* (10)
Infertile soil	0	63.02	79.23	142.25	1.60	9.01	5.73	8.15	53.6	376	6.57
Infertile soil	1.75	166.10	198.15	364.25	1.64	10.12	6.25	22.77	107.6	295	4.73
Intermediate soil	0	143.65	185.85	329.50	1.51	8.96	5.71	18.82	95.4	287	5.07
Intermediate soil	1.75	202.00	235.25	437.25	1.93	8.74	5.59	24.46	119.8	274	4.90
Fertile soil	0	200.50	216.75	417.25	1.59	9.48	5.69	23.74	109.2	262	4.60
Fertile soil	1.75	221.20	226.13	447.33	1.79	9.56	5.72	25.58	112.0	250	4.38

[1] For a detailed description of this experiment see pages 143 to 158. Four potometers were averaged for each group, except only three for fertile soil with manure.

[2] Stover includes stalk, leaves, and cob.

TABLE 74.—*Relation of ash content of Pride of the North corn plants to transpiration and fertility of soil. (The potometers were filled in 1911 and cropped to corn every year since, without refilling.) 1913 and 1914.*[1]

Description		Dry matter			Per cent ash			Total ash content	Total transpiration	Water transpired per gram total dry matter	Water transpired per gram ash content
Soil type	Moisture-free manure added	Grain	Stover[2]	Total	Grain	Stover	Total				
	Pounds	*Grams* (1)	*Grams* (2)	*Grams* (3)	*Per ct.* (4)	*Per ct.* (5)	*Per ct.* (6)	*Grams* (7)	*Kilos.* (8)	*Grams* (9)	*Kilograms* (10)
1913											
Infertile soil	0	8.37	78.96	87.33	1.12	7.38	6.78	5.92	62.4	714	10.53
Infertile soil	2.40	69.35	145.90	215.25	1.60	7.21	5.40	11.63	109.8	510	9.44
Intermediate soil	0	22.46	92.21	114.67	1.64	9.05	7.60	8.71	65.4	571	7.51
Intermediate soil	2.40	66.60	152.15	218.75	1.58	7.82	5.92	12.95	108.8	497	8.40
Fertile soil	0	75.32	148.93	224.25	1.46	9.61	6.87	15.41	122.3	545	7.94
Fertile soil	2.40	106.23	202.02	308.25	1.64	8.72	6.28	19.35	137.0	444	7.08
1914											
Infertile soil	0	13.86	62.39	76.25	1.61	8.39	7.15	5.45	37.2	487	6.82
Infertile soil	2.4	45.10	118.15	163.25	1.63	8.94	6.93	11.32	61.9	379	5.47
Intermediate soil	0	18.00	85.50	103.50	1.67	9.17	7.86	8.14	49.5	478	6.08
Intermediate soil	2.4	67.35	148.40	215.75	1.40	9.63	7.06	15.23	74.1	343	4.86
Fertile soil	0	49.47	117.53	167.00	1.58	9.47	7.13	11.91	63.7	382	5.35
Fertile soil	2.4	121.40	167.10	288.50	1.54	10.85	6.93	20.00	89.3	310	4.47

[1] For a detailed description of this experiment see pages 143 to 158.

[2] Stover includes stalk, leaves, and cob.

TABLE 75.—*Relation of ash content of corn to transpiration and fertility of soil. (Average of three fertility tests.*[1]*) 1913 and 1914.*

	Infertile soil	Inter-mediate soil	Fertile soil	Infertile soil and manure	Inter-mediate soil and manure	Fertile soil and manure
	(1)	(2)	(3)	(4)	(5)	(6)
Dry weight per plant (grams)	101.94	182.56	269.50	247.58	290.58	348.03
Total weight of ash (grams)	6.51	11.89	17.02	15.24	17.55	21.64
Ash content (per cent)	6.55	7.06	6.56	6.19	6.19	6.31
Total water transpired per plant (kilograms)	51.10	70.10	98.40	93.10	100.90	112.80
Total water used per gram dry matter (grams)	526.00	445.00	396.00	396.00	371.00	335.00
Water transpired per gram ash content (kilos.)	7.97	6.22	5.96	6.55	6.05	5.31

[1] These data are compiled from Tables 73 and 74. Twelve potometers were averaged for each group, except 11 plants for fertile soil with manure.

For a discussion of method used in compiling averages for 2 or more years, see page 42.

TABLE 76.—*Relation of ash content of Hogue's Yellow Dent corn plants to transpiration and moisture content of soil.*[1] *1913 and 1914.*

Description		Dry matter			Per cent ash			Total ash content	Total transpiration	Water transpired per gram total dry matter	Water transpired per gram ash content
Relative soil saturation	Moisture-free manure added	Grain	Stover[2]	Total	Grain	Stover	Total				
Per cent	*Pounds*	*Grams* (1)	*Grams* (2)	*Grams* (3)	*Per ct.* (4)	*Per ct.* (5)	*Per ct.* (6)	*Grams* (7)	*Kilos.* (8)	*Grams* (9)	*Kilograms* (10)
1913											
50	0	86.70	147.16	233.86	1.69	8.92	6.24	14.60	85.8	367	5.87
70	0	185.40	222.23	407.63	1.91	8.19	5.33	21.74	156.5	384	7.20
95	0	146.30	225.70	372.00	1.75	9.21	6.28	23.35	159.3	428	6.82
1914											
50	0	257.70	254.30	512.00	1.58	9.20	5.37	27.47	142.4	278	5.18
50	1.75	275.30	344.45	619.75	1.72	9.43	6.00	37.21	163.5	264	4.39
70	0	202.00	358.50	560.50	1.70	8.00	5.73	32.11	170.8	305	5.32
70	1.75	312.45	361.80	674.25	1.66	10.63	6.47	43.65	203.0	301	4.65
95	0	198.00	290.25	488.25	1.73	9.57	6.39	31.21	154.1	316	4.94
95	1.75	193.70	326.30	520.00	1.71	9.77	6.77	35.19	158.9	306	5.51
⅔ of 70[3]	0	216.45	276.05	492.50	1.64	9.12	5.83	28.73	128.7	261	4.48
⅔ of 70[3]	1.75	214.70	278.55	493.25	1.71	8.71	5.66	27.93	127.4	258	4.56

[1] For a detailed description of this experiment see pages 127 to 142.

[2] Stover includes stalk, leaves, and cob.

[3] The initial soil moisture content equalled 70 per cent and was reduced daily by restoring each day only two-thirds as much water as was transpired by the plants in soil constantly 70 per cent saturated.

Different relationships might be expected if the fertility should be increased indefinitely beyond the optimum condition.

EFFECT OF A DIFFERENCE IN SOIL MOISTURE CONTENT UPON RELATION OF TRANSPIRATION TO ASH CONTENT.

The ash content was determined for the plants in the 1913 and 1914 soil saturation experiments. These are described fully with additional data in pages 127 to 142. The ash relationships are given separately for each year in Table 76 and are summarized in Table 77. These summary data are obtained by first averaging the 1914 plants with and without manure in each degree of soil saturation. This average for 1914 is then averaged with the 1913 data.

TABLE 77.—*Summary showing relation of ash content of Hogue's Yellow Dent corn plants to transpiration and the moisture content of soil. Average for 1913 and 1914.*[1]

	50 per cent relative saturation	70 per cent relative saturation	95 per cent relative saturation
Dry weight per plant(grams)	399.87	512.50	438.07
Total weight of ash (grams)	23.47	29.81	28.28
Ash content (per cent)	5.96	5.72	6.43
Total water transpired per plant (kilos.)	119.38	171.70	157.90
Water transpired per gram dry matter (grams)	319.00	344.00	370.00
Water transpired per gram ash content (kilograms)	5.33	6.09	6.03

[1] Data compiled from Table 76.

EFFECT OF SIZE OF POTOMETER UPON RELATION OF TRANSPIRATION TO ASH CONTENT.

It is apparent from the data in Table 78 that the limitation of the amount of soil available for the plant has a marked influence upon the various relationships. The variations due to size of potometer were somewhat irregular, but there was a rather definite trend from the smaller to the larger potometers. In those potometers receiving no manure, the transpiration per gram ash content was, from the smallest to the largest potometers, 6.14, 5.70, 5.20, 5.50, 5.07, and 4.32 kilograms. Where manure was applied, these figures were 4.88, 6.03, 6.10, 5.43, 4.87, and 4.40 kilograms.

With an increase in the size of the potometers the total transpiration, the total dry matter, and the total ash content were

TABLE 78.—*Relation of ash content of corn plants to transpiration and size of potometers.*[1]

Description				Dry matter			Per cent ash			Total ash content	Total transpiration	Water transpired per gram total dry matter	Water transpired per gram ash content
Size of potometer	Wt. of soil (moisture free)	No. of potometers averaged	Manure added (moisture free)	Grain	Stover[2]	Total	Grain	Stover	Total				
Inches (1)	*Pounds* (2)	*Pounds* (3)	*Pounds* (4)	*Grams* (5)	*Grams* (6)	*Grams* (7)	*Per ct.* (8)	*Per ct.* (9)	*Per ct.* (10)	*Grams* (11)	*Kilos.* (12)	*Grams* (13)	*Kilograms* (14)
12x12	32.5	4	0	7.76	89.74	97.50	1.61	7.13	6.70	6.53	40.1	412	6.14
12x12	32.5	4	1.75	70.65	198.85	269.50	1.60	8.37	6.59	17.77	86.7	325	4.88
12x24	85.0	4	0	52.82	152.93	205.75	1.38	8.08	6.36	13.09	74.6	363	5.70
12x24	85.0	4	1.75	158.10	243.90	402.00	1.49	7.54	5.16	20.75	125.0	311	6.03
16x24	150.0	4	0	90.70	225.30	316.00	1.52	8.59	6.56	20.73	107.7	341	5.20
16x24	150.0	4	1.75	231.70	303.55	535.25	1.68	7.50	4.98	26.66	162.7	304	6.10
16x36	239.0	3	0	206.20	236.80	443.00	1.51	8.09	5.03	22.27	122.7	277	5.50
16x36	239.0	8	1.75	242.10	315.70	557.80	1.60	7.63	5.01	27.97	151.7	272	5.43
21x36	583.0	4	0	236.80	390.95	627.75	1.81	8.10	5.72	35.95	182.3	290	5.07
21x36	583.0	4	1.75	280.20	427.55	707.75	1.74	8.00	5.52	39.08	190.5	269	4.87
30x36	956.0	3	0	336.70	391.60	728.30	1.72	8.88	5.57	40.57	175.1	240	4.32
30x36	956.0	4	1.75	350.70	430.05	780.75	1.56	9.10	5.72	44.64	196.4	252	4.40

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[1] For a detailed description of this experiment see pages 54 to 67.

[2] Stover includes stalk, leaves, and cob.

rather regularly increased; the water used per gram dry matter was rather regularly decreased; and the per cent ash content and the amount of transpiration per gram ash content were somewhat irregularly decreased.

EFFECT OF KIND OF CROP AND VARIETY UPON RELATION OF TRANSPIRATION TO ASH CONTENT.

Ash determinations were made for all of the corn varieties described in pages 159 to 169, and are reported in Table 79.

Considerable variation exists in the ash relationships of the different varieties of corn, but there appears to be no absolute correlation between the percentage of ash, the amount of water transpired per gram ash content, or the transpiration per gram dry matter. The sunflowers possessed a high percentage of ash and water requirement per gram of ash and per gram dry matter. The two sorghum varieties were slightly lower in the amount of water transpired per gram ash content than was the corn. Of the 12 corn varieties, the Chinese corn and Roberts' hybrid, which was related to Chinese corn, had the lowest transpiration per gram ash content. Averaging together the five corn varieties with a water requirement per gram dry matter of 260 or above, and in a second group those varieties with a water requirement ratio of less than 260, we get the following relationships:

	First group	Second group
Water transpired per gram dry matter (grams)	276	249
Water transpired per gram ash content (kilograms)	5.01	4.29
Ash content (per cent)	5.53	5.82
Total dry matter (grams)	439	411

TABLE 79.—*Relation of ash content to transpiration, variety, and kind of crop. 1914.*[1]

Description	Dry matter			Per cent ash			Ash content	Total transpiration	Water transpired per gram total dry matter	Water transpired per gram ash content
	Grain	Stover[2]	Total	Grain	Stover	Total	Total			
	Grams (1)	*Grams* (2)	*Grams* (3)	*Per ct.* (4)	*Per ct.* (5)	*Per ct.* (6)	*Grams* (7)	*Kilos.* (8)	*Grams* (9)	*Kilograms* (10)
Rocky Mountain Dent corn from New York	179.40	232.60	412.00	1.84	8.43	5.56	22.91	110.4	268	4.82
Calico corn from North Platte, Nebraska	174.34	262.91	437.25	1.61	7.68	5.26	23.00	113.8	260	4.95
Wood's White Dent corn from New York	208.70	292.55	501.25	1.84	8.10	5.49	27.54	125.3	250	4.55
Martens' White Dent corn from Chadron, Nebraska	134.60	198.48	333.08	1.83	8.86	6.02	20.04	83.9	252	4.19
Pride of the North corn from Lincoln, Nebraska	222.70	223.80	446.50	1.66	8.66	5.17	23.08	102.8	230	4.45
University No. 3 corn from Lincoln	191.60	281.90	473.50	1.78	8.52	5.79	27.43	135.0	285	4.92
Hogue's Yellow Dent corn from Lincoln, Nebraska	242.10	315.70	557.80	1.60	7.63	5.01	27.97	151.7	272	5.43
Emerson's liguleless corn from Lincoln, Nebraska	135.00	178.25	313.25	1.54	9.43	6.03	18.89	92.7	296	4.91
Emerson's normal dent corn from Lincoln, Nebraska	145.00	182.25	327.25	1.71	8.53	5.51	18.03	81.2	248	4.50
Roberts' Kansas Dent × Esperanza × Chinese Hybrid corn	91.35	242.90	334.25	1.69	8.60	6.71	22.43	85.0	254	3.79
Sherrod's Kansas Dent corn from Kansas	195.30	283.70	479.00	1.66	8.54	5.74	27.47	123.2	257	4.48
Chinese corn from Kansas	174.50	284.17	458.67	1.58	8.85	6.09	27.94	114.2	249	4.09
Milo (sorghum)	263.90	323.10	587.00	2.88	8.11	5.76	33.80	150.9	257	4.47
Black Amber sorghum	67.90	109.60	177.50	4.04	9.62	7.48	13.28	54.5	307	4.10
Wild sunflower (*Helianthus annuus*)	167.50[3]	695.25	862.75	8.31	8.27	8.26	71.25	507.0	588	7.11

[1] For a detailed description of this experiment see pages 159 to 169.

[2] Stover includes stalk, leaves, and cob.

[3] The sunflower had the entire head, including the seed, weighed and ground together for ash determination.

CORRELATIVE RESPONSE OF LEAF STRUCTURE AND TRANSPIRATION, AS RELATED TO VARIETY, ACCLIMATIZATION, AND SOIL CONDITIONS.

Careful measurements of leaf thickness and the relative number of stomata per unit leaf-area were made with the corn and sorghum varieties grown in the 1914 variety and acclimatization test. The relative number of stomata was also determined for the corn plants grown in the different degrees of soil moisture and of soil fertility in 1914.

For these histological studies two leaf sections were taken by means of a Ganong leaf punch from each of three leaves of every plant. The leaves selected were the ear leaf and the leaf on either side. It was considered that these three central leaves would be fairly representative for the entire plant. The sections were taken in the widest portion of the leaf midway between the midrib and the margin. Since there were four duplicate potometers, 24 leaf samples were obtained for each variety or treatment. To determine the relative number of stomata, the number in 120 separate fields under the microscope was counted for each variety or treatment. To determine the epidermis and leaf thickness, 30 to 60 measurements were made for each. For stomata counts, the epidermis was stripped from the leaf. The thicknesses were measured from stained microtome sections of material imbedded in paraffin. The technique is explained in detail on pages 188 and 189.

By reference to Table 80 it will be seen that considerable variation existed between the different varieties in regard to the thickness of the leaf and of the epidermis and also in the number of stomata per unit leaf-area. There was, however, no apparent striking or consistent correlation between these histological coefficients and the transpiration rate per unit dry matter or per unit leaf-area of the different varieties. It is also evident from Tables 81 and 82 that there was no very striking response in the relative number of stomata to variation in either soil moisture or soil fertility. The reader is referred to the tables which follow for a summary of these relationships.

Some very interesting histological generalizations concerning corn may be drawn from the 11 varieties grown in the potometers in 1914. These are tabulated in Table 83.

TABLE 80.—*Summary of histological leaf measurements of corn and sorghums grown in the acclimatization and variety tests in potometers.*[1] *1914.*

Description	Dry matter per plant	Leaf-area per plant	Water requirement per		Thickness of			Per cent of total thickness of			Number of stomata per sq. mm.		
			Gram dry matter	Sq. in. leaf-area	Leaf	Upper epidermis	Lower epidermis	Upper epidermis	Lower epidermis	Total epidermis	Upper surface	Lower surface	Average
	Grams (1)	*Sq. in.* (2)	*Grams* (3)	*Grams* (4)	*Mu* (5)	*Mu* (6)	*Mu* (7)	*Per ct.* (8)	*Per ct.* (9)	*Per ct.* (10)	(11)	(12)	(13)
NEW YORK CORN[2]													
Rocky Mountain Dent..	412	841	268	131	188	29.2	24.8	15.5	13.2	28.7	85	102	93
Wood's White Dent....	501	1,103	250	114	216	35.2	27.2	16.3	12.6	28.9	74	86	80
WESTERN NEBRASKA CORN													
Calico...............	437	1,038	260	110	180	36.4	25.2	20.2	14.0	34.2	85	104	94
Martens' White Dent...	333	758	252	111	188	37.2	27.6	19.8	14.7	34.5	64	79	71
SPECIAL DROUTH RESISTANCE[3]													
Kansas Dent corn (Sherrod's)..........	479	924	257	133	180	25.2	22.8	14.0	12.7	26.7	64	90	77
Chinese corn..........	459	1,213	249	94	188	37.2	26.0	19.8	13.8	33.6	92	106	99
Esperanza.............	....	1,098	....	104	152	37.2	26.0	24.5	17.1	41.6	63	77	70
Roberts' hybrid........	334	948	254	90	184	34.0	26.4	18.5	14.3	32.8	84	108	96
MISCELLANEOUS CORNS													
Hogue's Yellow Dent...	558	1,321	272	115	180	32.0	27.2	17.7	15.1	32.8	64	77	70
Pride of the North.....	446	813	230	126	204	34.4	26.0	16.8	12.7	29.5	70	91	80
Emerson's liguleless.....	313	768	296	121	276	52.0	27.6	18.8	10.0	28.8	68	78	83
Emerson's normal dent.	327	710	248	114	208	33.2	24.8	15.9	11.9	27.8	93	101	97
SORGHUMS													
Amber sorghum........	177	....	307	....	188	44.0	28.4	23.4	15.1	38.5	91	128	110
Milo................	587	....	257	....	160	28.4	22.8	17.7	14.2	31.9	84	112	98
Average for 11 corns[4]...	418	949	258	114	200	35.1	26.0	17.6	13.2	30.8	77	93	85
Average for 2 sorghums.	382	....	282	....	174	36.2	25.6	20.5	14.6	35.2	87	120	104

[1] For further data concerning these crops see Tables 67 and 68, pages 164 and 165.

[2] The New York and western Nebraska varieties were chosen as representatives of corns acclimatized for many years respectively to the humid and semiarid atmospheric conditions of those two regions.

[3] Chinese and Esperanza corn have been credited with special marked drouth resistance. Roberts' hybrid was an attempt to introduce their drouth-resistant qualities to a standard Kansas Dent corn known as Sherrod's corn.

[4] Esperanza is not included in average, because the data are partially lacking.

TABLE 81.—*Summary of relation of varying degrees of soil moisture and of manure to the number of stomata, growth, and water requirements of corn. (Hogue's Yellow dent corn.) 1914.*[1]

Relative saturation	Manure added (moisture free)	Dry matter per plant	Leaf-area per plant	Water requirement per		Number of stomata per sq. mm.		
				gram dry matter	sq. in. leaf-area	Upper surface	Lower surface	Average
Per cent	*Pounds*	*Grams*	*Sq. in.*	*Grams*	*Grams*			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
50	0	512	1,407	278	101	65	84	74.5
50	1.75	620	1,304	264	125	69	87	78.0
70	0	560	1,433	305	119	59	69	64.0
70	1.75	674	1,488	301	136	65	80	72.5
95	0	488	1,399	316	110	60	76	68.0
95	1.75	520	1,236	306	129	65	81	73.0
$\frac{2}{3}$ of 70	0	492	1,222	261	105	61	78	69.5
$\frac{2}{3}$ of 70	1.75	493	1,105	258	115	75	99	87.0

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[1] For other data concerning these plants see Tables 55 to 58.

TABLE 82.—*Summary of relation of different degrees of soil fertility to number of stomata, growth, and water requirements of corn. (Pride of the North corn.) 1914.*[1]

Kind of soil	Manure added	No. of potometers averaged	Dry matter per plant	Leaf-area per plant	Water requirement per		Number of stomata per sq. mm.		
					gram dry matter	sq. in. leaf-area	Upper surface	Lower surface	Average
	Pounds (1)	*Grams* (2)	*Sq. in.* (3)	*Grams* (4)	*Grams* (5)	(6)	(7)	(8)	(9)
Infertile	0	4	142	495	376	108	62	80	71.0
Infertile	1.75	4	364	856	295	126	68	92	80.0
Intermediate	0	4	330	768	290	124	70	84	77.0
Intermediate	1.75	4	437	872	274	137	67	84	75.5
Fertile	0	4	417	889	262	123	66	84	75.0
Fertile	1.75	3	447	884	250	127	67	78	72.5

[1] For further data concerning these plants, see Tables 62 to 65.

TABLE 83.—*Summary of stomatal and epidermal relationships with corn.*

Number of stomata per square inch of upper epidermis	49,665
Number of stomata per square inch of lower epidermis	59,985
Total number of stomata per square inch of leaf	109,650
Average leaf-area per plant for 11 varieties (square inches)	949
Total number of stomata per plant	104,057,850
Average dimensions of stomatal aperture (microns)	25.6 x 3.5
Average area of stomatal aperture (square microns)	89
Area of average epidermis occupied by stomatal apertures (per cent)	.76
Area of leaf occupied by stomatal apertures in both epidermises (per cent)	1.52
(The stomatal aperture is practically closed at night and when the leaf is wilted.)	
Average thickness of leaf (microns)	200
Average thickness of upper epidermis (microns)	35.2
Average thickness of lower epidermis (microns)	26.0
Relative thickness of upper epidermis to leaf (per cent)	17.6
Relative thickness of lower epidermis to leaf (per cent)	13.2
Relative thickness of total epidermis to leaf (per cent)	30.8

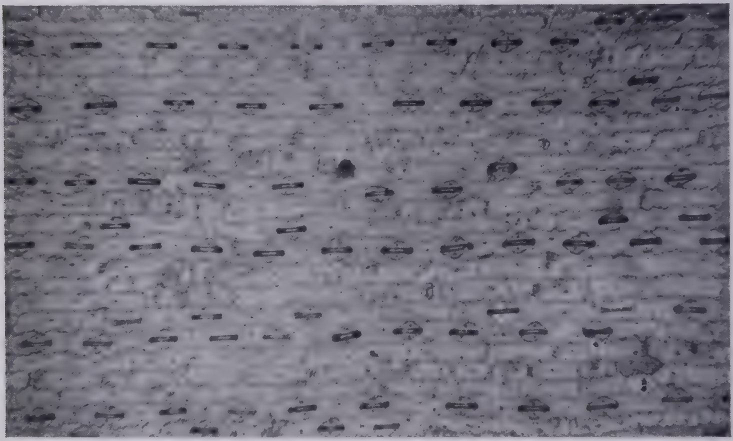

Fig. 23.—Microphotograph of 0.83 square millimeter of corn-leaf epidermis.

TISSUES CONCERNED IN THE TRANSPIRATION CURRENT OF CORN[1].

TECHNIQUE.

The material for the histological work in this paper was secured from plants in active growing condition in the field. The material for leaf sections was cut from the leaf by means of a punch. The fixing agent used was a water solution of 1 per cent of chromic acid and $\frac{1}{2}$ per cent of acetic acid. The specimens were allowed to remain in this solution 24 hours and were then washed 24 hours in running water. They were then transferred to 15, 35, 50, 70, 80, 95, and 100 per cent alcohol at intervals of about 2 hours, then to 25, 50, 75, and 100 per cent xylol at the same intervals. After thoro infiltration with paraffin, the specimens were imbedded and put away for sectioning. The material for stem work was preserved in alcohol and formol in the proportion of 95 c. c. of 50 per cent alcohol and 4 or 5 c. c. of 40 per cent formol. The stomata material was stripped from the leaf and plunged at once into 100 per cent alcohol.

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[1] References on the histology of the vegetative parts of the corn plant: Bessey (1889), Burtt-Davy (1914), Combs (1897), Harshberger (1897), Montgomery (1913), and Timiriazeff (1912).

The leaf sections were cut 10 to 15 microns thick and stained in safranin and light green. The safranin stain consisted of equal parts of a saturated water solution and a saturated alcohol solution.

The light green was a saturated clove oil solution. The stem sections were stained in the same safranin and light green. The stomata material was stained in Delafield's haematoxylin and eosin. The material was mounted in balsam for permanent slides.

A comparison of fresh material with permanent mounts showed very clearly that with the latter the chloroplasts in the cells of the chlorophyll-bearing bundle-sheath assumed an abnormal elongated shape and grouped themselves in an unnatural crescent arrangement about the outer edge of the cells. For this reason the chloroplasts have been drawn in these cells in the following plates as they occur in fresh material. It is of interest to observe the distinct difference in size, and reaction to the killing process, between the chloroplasts in the cells of the chlorophyll-bearing bundle-sheath, and those of the leaf parenchyma in general. All other tissues shown in the camera lucida drawings have been checked with fresh material and found to be normal.[1]

TISSUE STRUCTURE.

Plate I contains microphotographs showing the general character and arrangement of the tissues involved in the transpiration current of corn. Figure 1 is a vertical section of the root showing the root cap and the origin of the vascular strands. Figure 2 shows in cross section the specialized area of the corn root thru which the water ascends, for the most part, after its intake from the surrounding cells. The vascular tissue of the root is arranged in one circle around the central portion of the root. The origin of a lateral rootlet is seen in the figure. Figure 3 is a 1-5 sector of a small corn stem showing the scattered arrangement of the vascular strands. The cut ends of the vascular tubes may be seen in this figure. Water rises thru the vascular tubes of the stem and passes into the leaves thru the vascular bundles shown in Figure 4. Figure 4 is a cross section of part of a corn leaf. Here may be seen the two epidermal layers which are nearly impervious and serve to practically prevent water loss except that which passes thru the stomata, a number of which may be seen in section on both sides of the leaf. Figure 5 represents 1.3 square millimeters of lower epidermis. This shows the definite arrangement of the stomata in rows as well as the stomatal apertures thru which the internal water is evaporated into the air.

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[1] The author is indebted to Dr. Florence A. McCormick for suggesting a comparison of the fresh and permanently mounted specimens.

Plate II shows various studies of the epidermis, both upper and lower surfaces. With the exception of Figure 8 which is diagrammatic, all figures were made with the camera lucida. Figure 1 is a cross section of the upper epidermis, showing the relative size of normal upper epidermal cells and the relative thickness of the walls. Figure 2 is a longitudinal section showing the same features. Figure 3 and 4 are cross sections of the upper epidermis showing groups of enlarged cells to which has been attributed the seat of leaf curling in time of water scarcity. Figure 5 is a longitudinal section of these enlarged cells. Figure 6 is a cross section of the lower epidermis, showing normal cells. Figure 7 is a longitudinal view of the cells of the lower epidermis. Figure 8 is a surface view of the lower epidermis. This figure shows diagrammatically the arrangement of the epidermal cells and stomata in rows extending lengthwise of the leaf. The prominent nuclei in the cells of the epidermis as well as the subsidiary cells of the stomata, are evident. Figure 9 shows more in detail the relation of a single stoma and the surrounding epidermal cells. The incurving of the walls of the epidermal cells to meet the walls of the subsidiary cells is quite characteristic. Figure 10 is a single stoma as seen under an oil immersion lens. The prominent nuclei of the subsidiary cells as well as the chloroplasts located in the ends of the guard cells are features to be noticed. The number of plastids varies in different stomata. The aperture between the guard cells is the stoma proper, altho the whole structure is often referred to as the stoma. Figure 11 is a cross section of a stoma of the same magnification as Figure 10. This section is taken somewhere in the region of the two nuclei of the subsidiary cells. Figure 12 is a leaf hair, which is a single modified epidermal cell.

Plate III shows various studies of sections of the leaf. Figure 1 is a longitudinal section of a leaf in the region midway between two bundles. There is little differentiation in the corn leaf between the chlorophyll-bearing cells of the upper and lower surface of the leaf. The rather loose texture of the leaf with the relatively large air spaces is characteristic of a vertical section in this region. Figure 2 is the same kind of a section taken closer to the bundle, thru a row of the cells of the chlorophyll-bearing bundle-sheath. The texture of the leaf here is not so loose as in the region illustrated in the preceding figure. Figure 3 is a longitudinal view of a leaf thru the vascular bundle. Compact tissue relatively free from air spaces is always found in and immediately surrounding the bundles. A chlorophyll-bearing sheath of single-cell thickness is always a prominent feature in connection with a bundle. Figure 4 is a cross section of a leaf showing a single bundle. The compact chlorophyll-bearing tissue is here seen in cross section. The water-conducting tissue of the bundle is represented by three heavy walled tubes shown in cross section. The relationship of a stoma in connection with its underlying air chamber to the internal leaf tissue is here seen. Figure 5 is a cross section of two bundles showing a lateral connection between the water conduction elements of the bundles. This doubtless accounts for the fact that a bundle in a leaf may be cut without completely isolating the remainder of that bundle in respect to its water supply. Figure 6 is a cross section of one of the more prominent ribs of a corn leaf. The thick-walled protective tissue on both the upper and lower sides of the bundle is characteristic. Small bundles are completely surrounded by a chlorophyll-bearing sheath while large bundles such as this one are only partly encompassed.

Plate IV has two semidiagrammatic figures. Figure 1 is a three-plane view of a corn leaf. The view given here is the same as that of three walls of a box. The features shown are the same as those already explained in other figures, so that detail is not necessary. The three planes have not been drawn in perspective but merely assembled to show their relationship. Figure 2 is a two-plane view of a portion of stem, showing cross and longitudinal sections in their relative positions to each other. The longitudinal section view is taken midway between the large vascular elements which always show so prominently in any cross section view of corn bundles. The phloëm seen at *d* in cross section and *d* in longitudinal section consists of sieve tubes and numerous companion cells. This tissue is always located at one side of the water-conducting tubes.

DESCRIPTION OF PLATE I.

Fig. 1.—Longitudinal section of root tip. × 40.
Fig. 2.—Cross section of root some distance back of tip. × 40.
Fig. 3.—Cross section of small stem (1/5 sector). × 6.
Fig. 4.—Cross section of portion of leaf. × 40.
Fig. 5.—Surface view of lower leaf epidermis. × 40.

PLATE I.

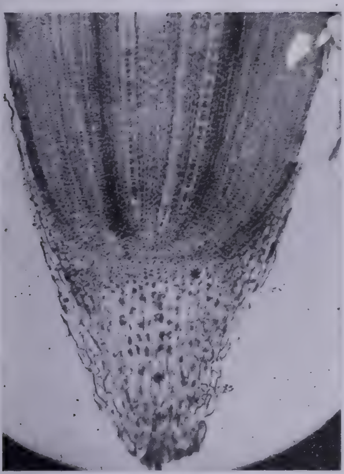

Fig. 1. × 40.

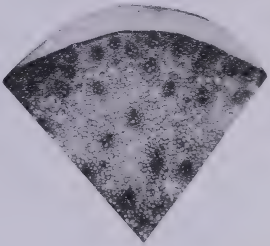

Fig. 3. × 6.

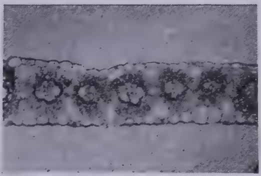

Fig. 4. × 40.

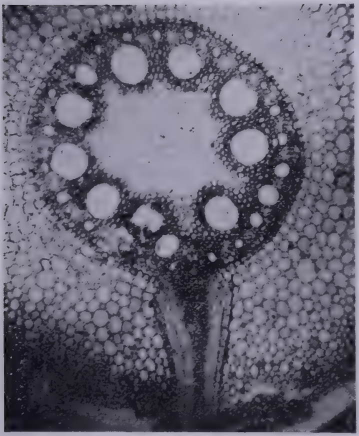

Fig. 2. × 40.

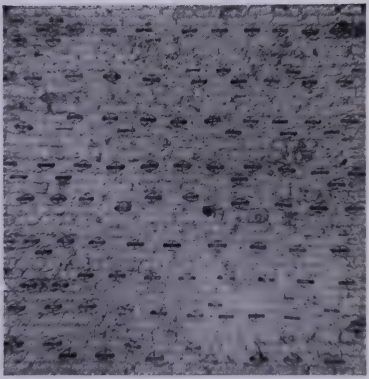

Fig. 5. × 40.

DESCRIPTION OF PLATE II.

Fig. 1.—Cross section of upper epidermis. × 233.
a, cuticula. *b*, cells of epidermis. *c*, chlorophyll-bearing tissue of leaf.
Fig. 2.—Longitudinal section of upper epidermis. × 233.
a, cuticula. *b*, cells of epidermis. *c*, chlorophyll-bearing tissue of leaf.
Fig. 3.—Cross section of upper epidermis. × 233. Group of 3 enlarged cells concerned in leaf rolling.
Fig. 4.—Cross section of upper epidermis. × 233. Group of cells as in Fig. 3, but with maximum development.
Fig. 5.—Longitudinal section of enlarged cells of upper epidermis. × 233.
Fig. 6.—Cross section of lower epidermis. × 233.
Fig. 7.—Longitudinal section of lower epidermis. × 233.
Fig. 8.—Diagrammatic drawing of lower epidermis. × 50.
a, cells of epidermis, surface view. *b*, stomata (arranged in rows). *c*, nucleus.
Fig. 9.—Portion of epidermis. × 233.
To show relation of cells to stoma. *a*, epidermal cell. *b*, stoma. *c*, nucleus.
Fig. 10.—Single stoma. × 500.
a, subsidiary cell, with prominent nucleus. *b*, guard cell. *c*, stoma proper (aperture). *d*, chloroplasts in guard cells. *e*, nucleus.
Fig. 11.—Cross section of stoma. × 500.
a, epidermal cell. *b*, subsidiary cell. *c*, guard cell. *d*, stoma proper (aperture).
Fig. 12—Epidermal hair. × 233.

PLATE II.

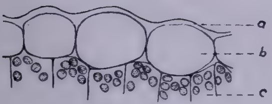

Fig 1 × 233

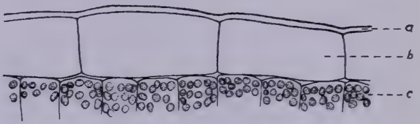

Fig 2 × 233.

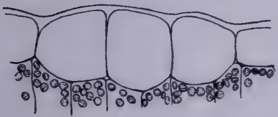

Fig. 3. × 233.

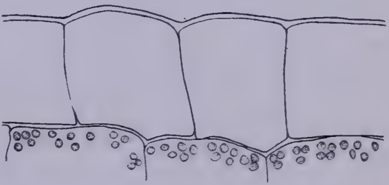

Fig 5 × 233.

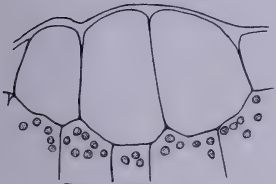

Fig. 4 × 233

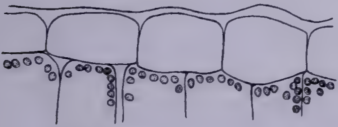

Fig. 6 × 233.

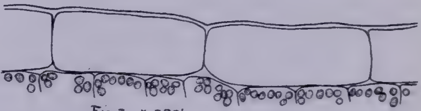

Fig. 7. × 233.

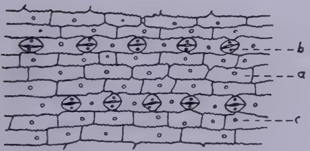

Fig 8 × 50

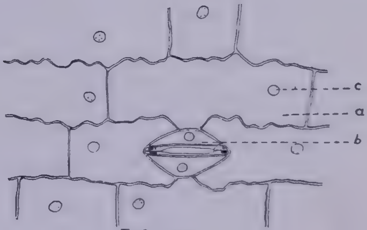

Fig 9 × 233.

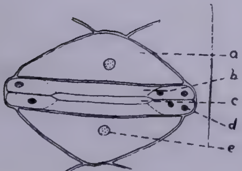

Fig 10. × 500.

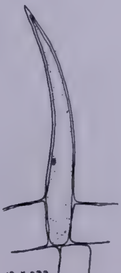

Fig. 12 × 233

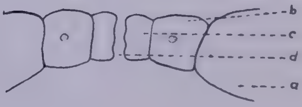

Fig. 11. × 500.

DESCRIPTION OF PLATE III.

Fig. 1.—Longitudinal section of leaf. × 233.
Section taken midway between two vascular strands. *a*, upper epidermis. *b*, lower epidermis. *c*, spongy chlorophyll-bearing tissue.

Fig. 2.—Longitudinal section of leaf. × 233.
Section taken thru chlorophyll-bearing bundle sheath. *a*, upper epidermis. *b*, lower epidermis. *c*, chlorophyll-bearing tissue of leaf. *d*, portion of chlorophyll-bearing bundle sheath.

Fig. 3.—Longitudinal section of leaf thru vascular strand. × 233.
a, upper epidermis. *b*, lower epidermis. *c*, *d*, chlorophyll-bearing tissue. *e*, phloëm. *f*, xylem elements of bundle. *g*, *h*, chlorophyll-bearing bundle sheath.

Fig. 4.—Cross section of leaf. × 233.
a, upper epidermis. *b*, lower epidermis. *c*, chlorophyll-bearing tissue. *d*, chlorophyll-bearing bundle sheath. *e*, phloëm. *f*, xylem. *g*, stoma. *h*, air space below stoma.

Fig. 5.—Cross section of leaf showing connection between vascular strands. × 233.

Fig. 6.—Cross section of one of larger leaf bundles. × 233.

PLATE III.

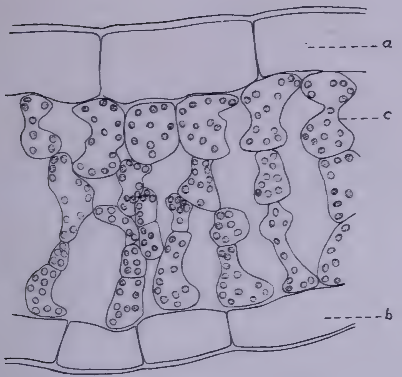

Fig 1 x 233

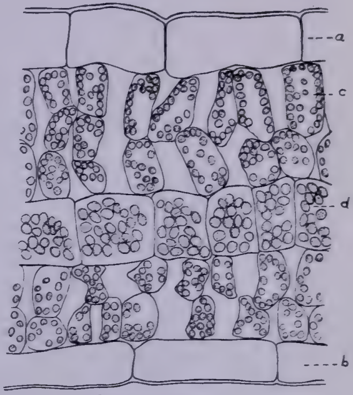

Fig. 2 x 233.

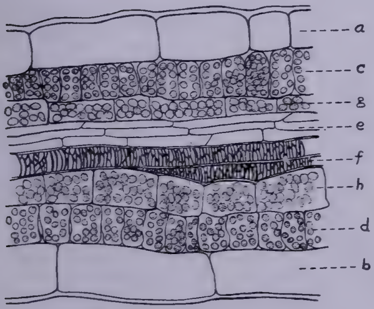

Fig 3 x 233.

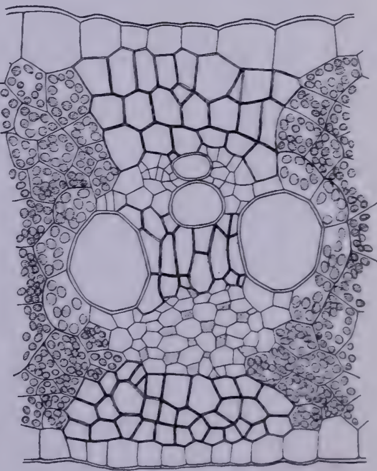

Fig. 6 x 233.

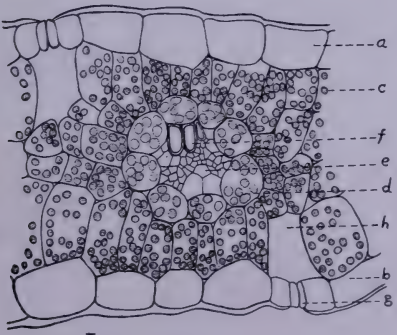

Fig. 4. x 233.

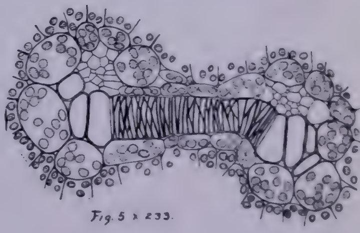

Fig. 5 x 233.

DESCRIPTION OF PLATE IV.

Fig. 1.—Three-plane view of leaf. × 233. Diagrammatic.

A, cross section of leaf.

a, upper epidermis. *b*, lower epidermis. *c*, chlorophyll-bearing tissue. *d*, phloëm of vascular strand. *e*, xylem of vascular strand. *f*, chlorophyll-bearing bundle sheath. *g*, cross section of stoma. *h*, air chamber beneath stoma.

B, longitudinal section of leaf.

a, upper epidermis. *b*, lower epidermis. *c*, chlorophyll-bearing tissue. *d*, phloëm of vascular strand. *e*, xylem of vascular strand. *f*, longitudinal section of stoma. *g*, air chamber beneath stoma. *h*, epidermal hair.

C, inside surface view of lower epidermis.

a, epidermal cell with nucleus. *b*, stoma.

Fig. 2.—Two-plane views of bundle of stem. × 233.

A, cross section.

a, side of bundle toward outside of stem. *b*, side of bundle toward inside of stem. *c*, large pitted vessel. *d*, supportive tissue. *e*, air cavity. *f*, parenchyma cells of pith. *g*, compressed protophloëm.

B, longitudinal section.

a, parenchyma cells of pith. *b*, phloëm cells of bundle. *c*, air space seen in longitudinal section. *d*, xylem elements of bundle.

PLATE IV.

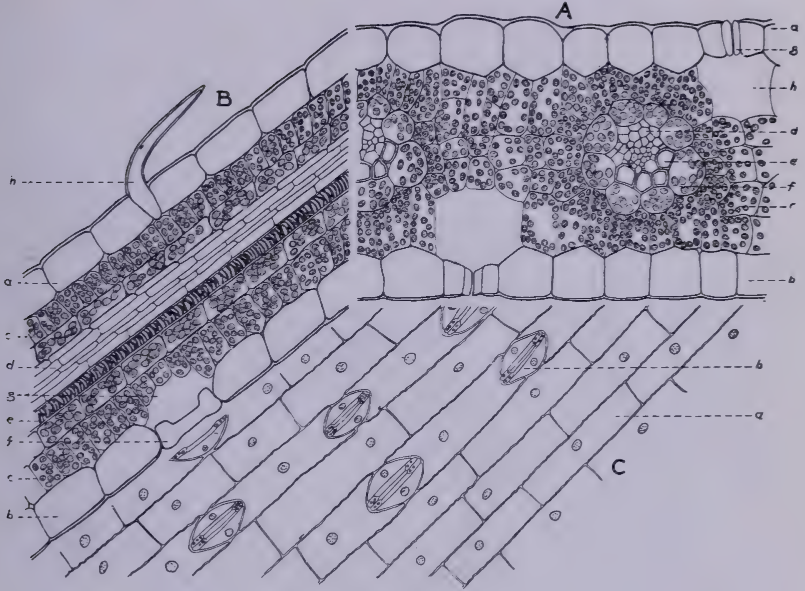

Fig. 1. × 233

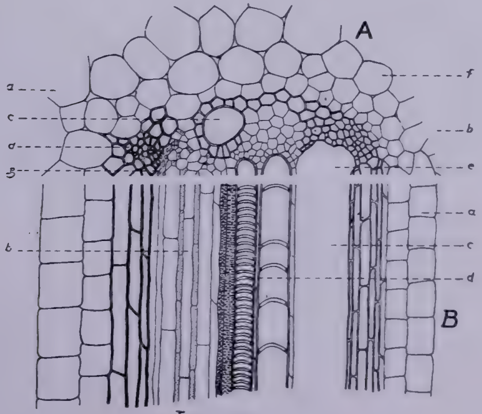

Fig. 2 × 233.

PART III.

APPLICATION.

The problem of conserving the water loss from the soil other than used by the plant does not concern us in this paper. It may be said, however, that because of the nature of the soil and the cultural treatments given it, much can be done toward conserving water for plant use (although this has been greatly over-emphasized —except the weed factor.) This is very important, since an abundance of soil moisture is so essential for crop production in all regions having only a moderately humid atmosphere. Much of the investigation and speculation which has been done concerning the economy of water in dry farming and irrigation has taken into consideration the relation of available water to crop yields, without determining the actual amount evaporated by the plant.

It is possible that some means can be devised whereby the actual water transpired by crops under given conditions will be reduced. There are two chief points of attack, namely, adjusting the external factors to the needs of the plant and, second, adapting the plant to the conditions.

The growth conditions of a cultivated crop may be either favorable or unfavorable for yields, with many intermediate degrees. Those factors which are most variable in any agricultural district are soil fertility, water supply, physical condition of the soil, and climate. There is also much variation in the plant characteristics of different crops and varieties. Each one of these may be a critical factor in crop production. A control of some one or more of these variable factors would naturally appear to give the greatest promise of controlling transpiration.

The problem is somewhat different for irrigated and nonirrigated conditions. Under irrigation the total amount of water may be adjusted to the requirements of the plant. Where the total available water supply is fixed by nature, no irrigation being possible, the problem is to produce the maximum crop (within profitable limits) on stated quantities of water.

The optimum condition for any one growth factor is to be regarded as that which is associated with the highest yield. As any one important condition becomes less favorable, others being equal, the yield is reduced. In the case of many factors there is a rather wide range of optimum condition.

SOIL FERTILITY.

A broad interpretation of our present knowledge would be that for any given locality those soil conditions relating to available fertility which are conducive for optimum growth result in production at the lowest water cost, or in other words the least water is required per unit dry matter. This does not mean, however, that under these optimum conditions less water is required per plant or per acre. In fact, it appears to mean just the reverse. For example, as you add manure to an infertile, unproductive soil, you may greatly reduce the water required per unit dry matter produced, but at the same time you also actually increase the total amount of water transpired. The ratio of water loss to dry weight is lower because the plants grow in a more normal manner. Anything below the optimum fertility approaches a pathological condition. In this condition the plants lack the thrift and vigor characteristic of a fertile soil, and consequently the elaboration of carbohydrates and the accumulation of dry matter are less for a given water usage. The plants grow more luxuriantly in fertile soil, having a greater leaf-area, and consequently each plant requires a greater total amount of available water. Under conditions where the rainfall is limited, what would be the result of adding fertility? It would not mean that the plants could endure dry weather better by requiring less water, but it would mean a greater total water requirement per plant, and the crops would tend to withstand the shortage of moisture less well than if no fertility had been added. The addition of manure to an infertile soil would not appear to offer any hope of growing crops in territories too dry to grow crops without it, by virtue of reducing the amount of water consumed by the individual plant, as is commonly stated, for in fact the total transpiration would be increased. Thus, in regions of limited rainfall where corn is now grown but suffers from lack of moisture, an application of manure or other fertilizer might be expected to cause even greater injury from a lack of moisture provided the same rate of planting was practiced, thus giving a greater total vegetable growth and greater leaf-area per acre from which water would evaporate.

COMBINATION OF INCREASED FERTILITY AND REDUCED RATE OF PLANTING.

There is one manner suggested by these experiments in which this reduced water requirement in the production of dry matter by the plant due to increased fertility may be taken advantage of under the above conditions of limited available moisture. If the plants were spaced farther apart upon the land so that a thinner stand would exist even after the greater amount of stooling which usually follows a reduced rate of planting has taken place, relatively more water would be available in the soil for the amount of growth it supports. Manure might then be applied, thereby combining for the individual plant a greater abundance of moisture and a greater production per unit water transpired resulting from increased fertility. There would doubtless be a counter tendency for more water to be lost by evaporation directly from the soil surface when the stand is reduced because of less protection given by the crop. This loss, however, would not be equal to the additional amount made available for the individual plant, and we might by such means hope to increase the efficiency of the total water available. But the writer believes that this increase of water efficiency is not due to any effect of the denser soil solution upon transpiration as a plant function, but simply to a more responsive growth of the plant. This would eliminate the conception that feeding the plant a more concentrated soil solution (or thick soup, as it is sometimes called) diminishes the need for, and actual amount of, transpiration.

It has been a very common experience of farmers in Nebraska and many other regions, that during relatively dry seasons, corn on alfalfa sod, except on irrigated or subirrigated land, produces a lower yield than on land which has not been in alfalfa. As is commonly said, "the corn burned up." The reason for this is twofold. (1) An old stand of alfalfa dries out the subsoil more than any other crop, and consequently a shortage of moisture exists for the corn to begin with. (2) Because of increased available fertility, corn on alfalfa sod makes a greater vegetative growth, having a greater leaf surface exposed to the climatic evaporation factors. As a result, there is a greater demand for moisture than on less fertile soil. This combined smaller supply of water and greater demand results in reduced yields during dry seasons. This difficulty could probably be overcome in a large measure, and the benefit of the increased fertility taken advantage of, by planting the corn at a thinner rate on alfalfa sod. Where corn is grown at the rate of three plants in hills 3.5 feet apart on normal soil, a stand of approximately two plants per hill should be suitable for rich alfalfa sod.

Listing corn on very fertile soil suggests itself as a rational practice. Listing tends to reduce or stunt the vegetative growth without proportionately reducing the ear development, and thereby less vegetative surface is exposed to the action of a drying atmosphere.

Another suggestion of possible practical value under semiarid conditions is that of Cunningham (1914) to space the corn rows twice as far apart as is commonly practiced, with double the normal number of plants in the row. The principle involved is that the plants will be reduced in vegetative growth because of competition, and the roots may continue to grow into the moister soil between the rows.

Our experimental data concerning the effect of increased fertility also suggest that it may be practicable on very fertile soil to grow a smaller variety of corn. The increased fertility will result in production at a relatively low water cost, while the total amount of water transpired will be held within reasonable limits by avoiding a luxuriant vegetative growth. These suggestive methods appear encouraging and are deserving of thoro investigation in practical field tests.

Our experience would indicate that much corn is planted at too thick a rate. The reduced yields from the thicker rates are due primarily, under our conditions, to a shortage of moisture, and secondarily to a shortage in available fertility for so large a number of plants. Farmers in the drier regions of the Great Plains area have recognized this principle and their rate of seeding is markedly lower than is practiced in more humid sections. Ordinarily the reduction in total water used will not be proportional to the reduction in stand, because of greater vegetative growth when plants are more favored.

MOISTURE CONTENT OF SOIL

The fact that a shortage of moisture below the optimum for the individual plant reduces the total water requirement and somewhat reduces the water requirement per unit dry matter of crop has no great practical value for application. This reduction cannot be brought about without a reduction in yield.

Soil with a surplus of moisture needs drainage. An overabundance of soil moisture reduces the yield. This is doubtless due to some injurious effect which decreases the amount of available fertility.

Under irrigation, there is no advantage in applying a surplus of water. Water will not take the place of soil fertility, nor is the common saying true that fertility may replace water. Increased fertility merely causes a more responsive growth, which is a factor in plant nutrition and not in transpiration. An excessive application of water results in a greater amount being transpired per unit dry matter produced than under optimum moisture content, but this is due, in part at least, to a less normal growth. The largest total amount is used under optimum soil moisture, when the largest yield is also harvested. There may be a large variation in the water content without materially affecting the growth relationships. Thus, the lowest soil saturation conducive to maximum growth is the most practical, for then less water is lost by surface evaporation than with a wetter soil.

CLIMATIC FACTORS.

It has been sufficiently demonstrated that the water requirements vary greatly with the climate. A low annual rainfall in a region with a cool, humid, "wind-still" climate would go as far as a much larger rainfall in a region where the air, at least during the growing season, is dry, hot, and windy. This is due to a lower value of the climatic water-dissipating influences. In regard to this, Briggs and Belz (1910) show in connection with studies of Shantz (1911), that the natural vegetation is a good index to crop production as related to climate. Short grass, consisting chiefly of buffalo grass and grama grass, is typical of semiarid conditions, such as found in the Great Plains area of the United States. A strip of short grass extends from Montana to Texas, limited on the west by drouth and on the east by competition with other grasses. In Montana the annual rainfall is 14 inches, while in Texas it is 21 inches. The difference of 7 inches in rainfall represents the additional amount of rainfall needed to offset the increased evaporation. Thus, we see that the necessary supply of available water for crop production cannot be measured by the rainfall without also knowing the evaporation rate, which Briggs and Belz (1910) have shown to vary from 24 to 72 inches annually from a free water surface in different parts of this country. Prospective settlers should keep in mind that in regions of low annual rainfall and high evaporation rate, the transpiration rate is also very high, working double hardships for crop production. In some sections, the evaporation rate is subject to great temporary acceleration from strong hot winds. A few hours of hot winds, coming as they are apt to do in periods of drouth, seem to be more fatal to crops, particularly corn, than are as many days of drouth minus the hot winds.

The evaporation from a shallow free water surface is affected by atmospheric conditions in a manner rather similar to the evaporation from the plant. Thus, knowing the free water evaporation during the growing season may be an index as to the relative amounts of water transpired in crop growth in any given locality. This explains why crops may be grown in the Northwest on lower rainfall than in the south central portion of the United States. A knowledge of the evaporation rate of a region is almost as important as to know the rainfall. The new meteorological term, "effective precipitation," covers this combination of factors.

ADAPTATION OF PLANTS.

The production of plants adapted to meet the requirements for a low transpiration rate offers a field of great possibilities. Under this may be included the testing and selection of established varieties already well adapted, and also the selection, within a variety, of strains possessing certain characters, or the creation by breeding of new characters correlated with low relative water consumption. It is well known that some plants are especially adapted to dry and others to humid conditions. For instance, the grain sorghums are well suited for dry farming. Just what characters fit them for this purpose is not fully known. Results with two of these crops, Milo and Amber sorghum, reported in this bulletin indicate that these crops do not have a lower water requirement in the production of dry matter than does corn under favorable moisture conditions. The work to date has been too limited to draw final conclusions. It may be possible that these dry land agricultural plants approach the condition of the desert plants described by Fitting (1911), which possess a high osmotic pressure and are able as a consequence to extract moisture from a comparatively dry soil in which the water films are very thin. Experiments have now been planned which should give definite information concerning this. It is evident from relative histological studies of the leaves of several sorghums and corns that the former have no special leaf structural adaptation for reducing the transpiration below that of corn. It has been observed under field conditions that sorghums appear to possess the power of entering into a more or less dormant stage when growth conditions become very unfavorable, as in time of a very dry spell, and renew growth without having been greatly injured when rains come. A plant possessing this power would have a great advantage. Frequently, under Nebraska conditions, several days of very severe dry, hot, windy weather may greatly reduce the yield of corn, because the evaporation rate is more rapid than the roots can supply, due to low soil-moisture content, and the corn plant is unable to go thru such a period without injury. It is these few outstandingly severe days that are especially injurious to most crops.

Merely to know the water requirement per pound of dry matter is not necessarily an index as to whether a crop is suited to drouth conditions. A kind of crop with a relatively high water requirement per pound of dry matter may normally produce a small tonnage per acre, and consequently the total water transpired be no higher than with another kind of crop having a relatively low water requirement.

It appears that the best means of securing crops definitely suited to dry farming conditions is actually to grow and compare them under those conditions.

WEEDS.

One of the most practical cultural treatments which a farmer can give his crops is the reduction of weeds. Weeds require water and fertility the same as does the crop, and where a shortage of moisture exists the crop is certain to suffer from the presence of weeds. Weeds use moisture in proportion to their number and size. Wild sunflowers grown in these experiments consumed as much moisture individually as an entire hill of three large corn plants:

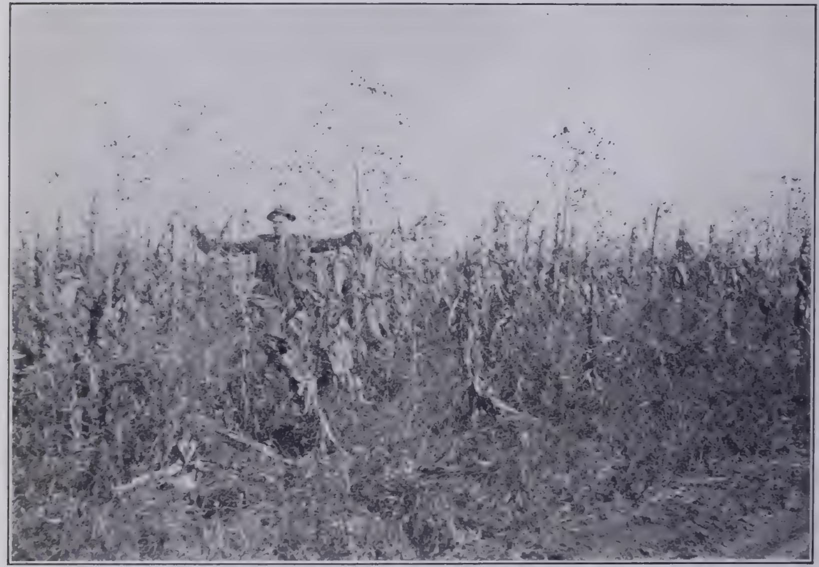

Fig. 24.—A field of corn which had been robbed of moisture by sunflowers and pig weeds. 1914.

WATER USED PER ACRE.

Experience with potometer and field tests would indicate that caution must be taken in applying the results from potometer studies to general farm practice.

It is impossible to estimate from potometer experiments the exact amount of water used per acre by a given crop under field conditions. The amount of available soil fertility, soil moisture, and other conditions in potometers never are and probably cannot be made to be strictly comparable to field conditions. This fact does not, however, prevent the establishment of general principles concerning the response of the plant to variable conditions under control in potometers nor concerning the relative water requirement of different crops.

(1) It was seen in Table 1 that as an average for four years the potometer plants had 5 per cent greater leaf-area and weighed 21 per cent more than the average of plants grown in the field at the rate of two plants per hill or 7,112 plants per acre, during three years, and three plants per hill during one year. Assuming that a corn plant in the potometers used as an average the same amount of water (132 kilograms) as was used by a corn plant in the field spaced two plants per hill, in hills 3.5 feet apart, we find that an acre of such corn would use 9.14 acre-inches of water. It is fairly certain that the total amount of water used per plant would not be greater under field conditions than the above figure.

With the customary rate of three plants per hill, the total water transpired per acre would doubtless be greater, altho not proportional to the increase in the number of plants unless sufficient available fertility and soil moisture were present to support fully the increased number. The increased self-protection of a thicker stand would probably tend to reduce transpiration.

(2) The 5-year average water requirement per pound of ear, as given in Table 31, is seen to be 629 pounds. Allowing 16 per cent for cob, we have a water requirement of 750 pounds per pound dry weight of grain. Assuming a 50-bushel yield of moisture-free grain, 1,050 tons or 9.3 acre-inches of water would be used, which is practically the same result as obtained by the previous method of calculation. The actual average yield of moisture-free corn at the Experiment Station during the past five years has been 37 bushels per acre, grown three plants per hill. According to the method just discussed, this yield would have had a water requirement of 6.9 acre-inches. This amount is evidently too low, since it does not take into consideration the water used by barren stalks, which are ordinarily rather numerous. The proportion of ear to stalk was also lower in the field than in the potometers. The average yield of moisture-free corn at the Experiment Station during 13 years has been 46 bushels per acre.

(3) The amount of water used in the production of a given yield of grain in potometers cannot be applied directly to the grain yield under field conditions without qualifications, because there are so many variable factors, all of which affect the water requirement.

We would probably not be far wrong in estimating the average water requirement of corn in eastern Nebraska at 9 inches of rainfall, which amount fluctuates greatly, of course, in different years. The average annual precipitation in eastern Nebraska is approximately 28 inches, two-thirds of which is lost in ways other than by transpiration from the corn crop.

LITERATURE CITED.

Cited in this bulletin on page—

ABBE, CLEVELAND.
1905. First report on the relations between climates and crops. (U. S. Department of Agriculture, Weather Bureau, Bul. 36)...20

BRIGGS, L. J., and BELZ, J. O.
1910. Dry farming in relation to rainfall and evaporation. (U. S. Department of Agriculture, Bureau of Plant Industry, Bul. 188, 71 pp.)...204

BRIGGS, L. J., and SHANTZ, H. L.
1913a. The water requirement of plants. I. Investigations in the Great Plains in 1910 and 1911. (U. S. Department of Agriculture, Bureau of Plant Industry, Bul. 284, 49 pp.).27, 29, 32, 36, 87, 159
1913b. The water requirement of plants. II. A review of the literature. (U. S. Department of Agriculture, Bureau of Plant Industry, Bul. 285, 96 pp.)...20, 87, 159
1914. Relative water requirement of plants. (U. S. Department of Agriculture, Journal of Agricultural Research, v. 3, no. 1.)....27, 32, 34, 36, 67, 87, 143, 159
1915. Effect of frequent cutting on the water requirement of alfalfa and its bearing on pasturage. (U. S. Department of Agriculture, Bureau of Plant Industry, Bul. 228, 5 pp.)...36

BURGERSTEIN, ALFRED.
1887. Materialien zu einer Monographie betreffend die Erscheinungen der Transpiration der Pflanzen. (Vienna, Zoologische-Botanische Gesellschaft. Verhandlungen, v. 37, pp. 691-782.)....20
1889. Materialien zu einer Monographie betreffend die Erscheinungen der Transpiration der Pflanzen. 2. Theil. (Vienna, Zoologische-Botanische Gesellschaft, v. 39, pp. 399-463.)...20
1901. Materialien zu einer Monographie betreffend die Erscheinungen der Transpiration der Pflanzen. 3. Theil. (Vienna, Zoologische-Botanische Gesellschaft. Verhandlungen, v. 51, pp. 49-106.)...20
1904. Die Transpiration der Pflanzen. (Jena, 283 pp.)...20

BESSEY, C. E.
1889. Botany. (New York, p. 41.)...188

BURTT-DAVY, JOSEPH.
1914. Maize. (Lond., pp. 76-77.)...188

CANNON, W. A.
1905. A new method of studying the transpiration of plants in place. (Bul. Torrey Botanical Club, v. 32, p. 515.)...23

COMBS, ROBERT.
1897. Histology of the corn leaf. (Iowa Academy of Sciences, Proceedings, v. 5, pp. 204-208.)...188

COULTER, J. M., BARNES, C. R., and COWLES, H. C.
1910. Textbook of botany. (N. Y. 1910, 2 v.)...19

CUNNINGHAM, C. C.
1914. A new method of growing corn. (Journal of The American Society of Agronomy, v. 6, no. 2, pp. 84-88.)...202

DASZEWSKI, A. VON.
1900. Der Einfluss des Wassers und der Düngung auf die Zusammensetzung der Asche der Kartoffel Pflanze. (Journal für Landwirtschaft, v. 48, pp. 223-249.)...36, 170

Cited in this bulletin on page—

EBERT, OSCAR.
1889. Die Transpiration der Pflanzen und ihre Abhängigkeit von äusseren Bedingungen. (Marburg, 100 pp.)....................20

EHLERS, J. H.
1911. The temperature of leaves of Pinus in winter. (American Journal of Botany, v. 2, no. 1, pp. 32-70.)....................116

FEST, FRANZ.
1908. Ueber den zeitlichen Verlauf der Nährstoffaufnahme und Trockensubstanzproduction bei der Buschbohne unter verschiedenen Düngungs- und Witterungsverhältnissen. (Journal für Landwirtschaft, v. 56, Heft 1, pp. 1-47.)....................33, 36

FITTING, HANS.
1911. Die Wasserversorgung und die osmotischen Druckverhältnisse der Wüstenpflanzen. (Zeitschr. für Bot., 3, pp. 209-275.)...205

FITTBOGEN, J.
1873. Untersuchung über das für eine normale Produktion der Haferpflanze nothwendige Minimum von Bodenfeuchtigkeit, sowie über die Aufnahme von Bestandtheilen des Bodens bei verschiedenem Wassergehalt desselben. (Landwirtschaftliche Jahrbücher, v. 2, pp. 353-371.)........................36, 87, 170

FORTIER, S.
1902. Soil moisture in relation to crop yield. (Montana Agricultural Experiment Station, 9th Annual Report.)....................36

HALES, STEPHEN.
1727. Essays. Vegetable Staticks (London)....................20

HARRIS, F. S.
1914. Effects of variations in moisture content on certain properties of a soil and on the growth of wheat. (Cornell University, Agricultural Experiment Station, Bul. 352, 63 pp.)..............36

HARSHBERGER, J. W.
1897. Maize. (University of Pennsylvania, Contributions from the Botanical Laboratory, v. 1, pp. 79-85.)......................188

HASSELBRING, HEINRICH.
1914a. Relation between the transpiration stream and the absorption of salts. (Botanical Gazette, v. 57, no. 1, pp. 72-73.)....36, 170
1914b. Effect of shading on the transpiration and assimilation of the tobacco plant in Cuba. (Botanical Gazette, v. 57, no. 4, pp. 257-286.)..36, 87, 170

HEINRICH, REINHOLD.
1894. Ueber die Wassermengen welche die Haferpflanze aus verschiedenen Nährstoff-Concentrationen während ihre Vegetationszeit verbraucht. (Rostock, Versuchs-Station. 2. Bericht, pp. 170-174.)....................................36, 87, 143

HELLRIEGEL, F. H.
1883. Verhältnis zwischen Produktion und Verdunstung.—Wie viel Wasser verbraucht eine Pflanze während der Erzeugung von einem Gramm Trockensubstanz durchschnittlich? (Beiträge zu den Naturwissenschaftlichen Grundlagen des Ackerbaus. Braunschweig, pp. 622-664.)...............27, 36, 54, 87, 143, 159

IL'ENKOV, P. A.
1865. Einige Versuche zur Bestimmung des Einflusses welchen die Bodenfeuchtigkeit auf die Vegetation ausübt. (Annalen der Chemie und Pharmacie, v. 136, n. D., v. 60, Heft 2, pp. 160-165.)..36, 170

Cited in this bulletin on page—

KHANKHOJE, P.
1914. Some factors which influence the water requirements of plants. (Journal of the American Society of Agronomy, v. 6, no. 1, pp. 1-23.) 36

KIESSELBACH, T. A.
1910. Transpiration experiments with the corn plant. (Nebraska Agricultural Experiment Station, 23d Annual Report, pp. 125-139.) 19, 36, 50, 87, 143

KIESSELBACH, T. A., and MONTGOMERY, E. G.
1911. The relation of climatic factors to the water used by the corn plant. (Nebraska Agricultural Experiment Station, 24th Annual Report, pp. 91-107.) 19, 36, 44, 87, 88

KING, F. H.
1892. The amount of water required to produce a pound of barley, oats, and corn in Wisconsin. (Wisconsin Agricultural Experiment Station, 8th Annual Report, pp. 124-131.) 34, 36, 159
1893. Amount of water required to produce a pound of dry matter in barley, oats, corn, clover, and peas in Wisconsin. (Wisconsin Agricultural Experiment Station, 9th Annual Report, pp. 94-100.) 34, 36, 143, 159
1894. Amount of water required to produce a pound of dry matter in Wisconsin. (Wisconsin Agricultural Experiment Station, 10th Annual Report, pp. 152-159.) 34, 36, 143, 159
1895. Number of inches of water required for a ton of dry matter in Wisconsin. (Wisconsin Agricultural Experiment Station, 11th Annual Report, pp. 240-248.) 34, 36, 67, 159
1905. Relative rates of evaporation at stations in four States from soil surface saturated by capillarity, and from corn. (U. S. Department of Agriculture, Bureau of Soils, Bul. 26, pp. 192-198.) 36, 87

KOLKUNOV, V.
1905. K. Voprosu O V'ïrabotkie V'ïnosliv'ïkh K Zasukham Rass Kul'turn'ïkh Rasteniĭ. Anatomo-Fizïologicheskïi͡a I Biometricheskïi͡a Izsliedovanïi͡a. (Kiev', 82 pp.) 36

LAWES, J. B.
1850. Experimental investigation into the amount of water given off by plants during their growth. (Journal, Horticultural Society, London, v. 5, pp. 38-63.) 36, 143, 159, 170

LEATHER, J. W.
1910. Water requirements of crops in India. (Memoirs of the Department of Agriculture in India. Chemical Series, v. I, no. 8, pp. 133-184.) 28, 36, 54, 87, 143, 159
1911. Water requirements of crops in India. (Memoirs of the Department of Agriculture in India. Chemical Series, v. I, no. 10, pp. 203-281.) 27, 28, 36, 54, 67, 87, 143, 159

LIEBSCHER, GEORG.
1895. Untersuchungen über die Bestimmung des Düngerbedürfnisses der Ackerböden und Kulturpflanzen. (Journal für Landwirtschaft, v. 43, Heft 1, pp. 49-216.) 36, 67, 143

LIVINGSTON, B. E.
1911. The relation of the osmotic pressure of the cell sap in plants to arid habitats. (Plant World, v. 14, no. 7, pp. 153-164.) 156
1912. Resistance offered by leaves to transpirational water loss. (Johns Hopkins University. Circ. 242, pp. 11-13.) 23
1913. Resistance offered by leaves to transpirational water loss. (Plant World, v. 16, no. 1, pp. 1-44.) 23

Cited in this bulletin on page—

LIVINGSTON, B. E., and BROWN, W. H.
1912. Relation of the daily march of transpiration to variation in the water content of foliage leaves. (Botanical Gazette, v. 53, pp. 309-330.) 100

MAERCKER, MAX.
1896. Ueber die Wirkung der Kalisalze auf Sandboden. (Deutsche Landwirtschafts-Gesellschaft, v. 20, pp. 7-30.) 36, 143

MARIÈ-DAVY, E. H.
1874. Note sur la quantité d'eau consommée par le froment pendant sa croissance. (Paris, Académie des Sciences. Comptes Rendus, v. 79, pp. 208-212.) 36, 143
1875. Évaporation du sol et des plantes. (Montsouris, l'Observatoire Municipal, Annuaire, pp. ———.) 36, 143
1876. Évaporation, transpiration. (Annuaire Météorologique de l'Observatoire de Montsouris, pp. 374-388.) 36, 143

MERGET, A.
1878. Sur les Fonctions des Feuilles. Rôte des Stomates dans l'Exhalation et dans l'Inhalation des Vapeurs aqueuses par les Feuilles. (Compt. Rend. de l'Acad. des Sci. de Paris, v. 87, p. 293.) 23

MONTGOMERY, E. G.
1911a. Correlation studies of corn. (Nebraska Agricultural Experiment Station, 24th Annual Report, pp. 150-159.) .. 19, 36, 43,48
1912. Methods of determining the water requirements of crops. (Journal of the American Society of Agronomy, v. 3, pp. 261-283.) 20
1913. The corn crops. (New York, p. 34.) 188

MONTGOMERY, E. G., and KIESSELBACH, T. A.
1912. Studies in water requirements of corn. (Nebraska Agricultural Experiment Station, Bul. 128, 15 pp.) 19, 37, 87, 143

OHLMER, W.
1908. Ueber den Einfluss der Düngung und der Bodenfeuchtigkeit bei gleichem Standraum auf die Anlage und Ausbildung der Aehre und die Ausbildung der Kolbenform beim Göttinger begrannten Squarehead-Winterweizen. (Journal für Landwirtschaft, v. 56, Heft 2, pp. 153-157.) 37, 143

PFEIFFER, THEODOR; BLANCK, EDWIN; and FLUEGEL, M.
1912. Wasser und Licht als Vegetationsfaktoren und ihre Beziehung zum Gesetze von Minimum. (Die Landwirtschaftlichen Versuchs-Stationen, v. 76, pp. 169-236.) 37, 87, 143

POWERS, W. L.
1914. Irrigation and soil-moisture investigations in western Oregon. (Oregon Agricultural Experiment Station, Bul. 122, 110 pp.) 23

PREUL, FRANZ.
1908. Untersuchungen über den Einfluss verschieden hohen Wassergehaltes des Bodens in den einzelen Vegetationsstadien bei verschiedenem Bodenreichtum auf die Entwickelung der Sommerweizenpflanze. (Journal für Landwirtschaft, v. 56, Heft 3, pp. 229-278.) 37, 143, 170

ROBERTS, H. F., and FREEMAN, GEO, F.
1908. Alfalfa breeding: materials and methods. (Kansas Agricultural Experiment Station, Bul. 151, pp. 90-98.) 23

Cited in this bulletin on page—

Schroeder, M. R.
1896. Razvitǐe i isparenǐe iachmeaea pri razlichnoĭ vlazhnosti i pitatel nosti substrata. Izviestüa Moskoskago sel Skokhozi͡aĭstvennago Instituta, god 2, kniga 1 (Annales, Institut Agronomique, Moscou, ann. 2, livr. 1, pp. 188-226.) 37, 143

Seelhorst, Conrad von.
1899. Ueber den Wasserverbrauch der Haferpflanze bei verschiedenem Wassergehalt und bei verschiedener Düngung des Bodens. (Journal für Landwirtschaft, v. 47, Heft 4, pp. 369-378.) 37, 143
1906. Ueber den Wasserverbrauch von Roggen, Gerste, Weizen, und Kartoffeln. (Journal für Landwirtschaft, v. 54, Heft 4, pp. 316-342.) 37, 143, 159
1908. Berichtigung zu dem Aufsatz: Ueber den Wasserverbrauch von Lupinen im Herbst 1906, usw., im Journal für Landwirtschaft 1908, S. 199 u. ff. (Journal für Landwirtschaft, v. 57, pp. 111-112.) 33, 37, 159
1910a. Der Wasserverbrauch von Wiese und Weide. (Journal für Landwirtschaft, v. 58, Heft 1, pp. 83-88.) 33, 143
1910b. Wasserverbrauch von Roggen auf Sandboden. (Journal für Landwirtschaft, v. 58, Heft 1, pp. 89-92.) 37

Seelhorst, C. von, and Dr. Muether.
1905. Beitrage zur Lösung der Frage nach dem Wasserhaushalt im Boden und nach dem Wasserverbrauch der Pflanzen. (Journal für Landwirtschaft, v. 53, Heft 3, pp. 239-268.) 37, 87

Seelhorst, C. von, and Buenger, J.
1907. Versuche mit Sommerweizen. (Journal für Landwirtschaft, v. 55, Heft 3, pp. 246-260.) 37, 54, 143

Shantz, H. L.
1911. Natural vegetation as an indicator of the capabilities of land for crop production in the Great Plains area. (U. S. Department of Agriculture, Bureau of Plant Industry, Bul. 201.) 204

Shreve, E. B.
1914. Daily march of transpiration in a desert perennial. (Carnegie Institution of Washington. Publication 194, 64 pp.) 116

Sleskin, P.
1908. X'voprosu ŏ raskhodie vody sakharnoĭ soekloĭ. Zhurnal Opytnoi Agronomu. (Russisches Journal für Experimentelle Landwirtschaft, t. 9, pp. 474-482.) 37

Sorauer, Paul.
1880. Studien über Verdunstung. (Forschungen auf dem Gebiete der Agrikultur Physik, v. 3, pp. 351-490.) 37, 87
1883. Nachtrag zu den "Studien über Verdunstung." (Forschungen auf dem Gebiete der Agrikultur-Physik, v. 6, pp. 79-96.) 37, 143, 159

Stahl, E.
1894. Einige Versuche über Transpiration und Assimilation. (Botan. Zeitung, v. 52, pp. 117-145.) 23

Thom, C. C.
1913. Some factors affecting the duty of water in dry farming. (The Washington Agriculturist, v. 6, no. 4, pp. 7-10.) .. 33, 37, 143, 159

Cited in
this bulletin
on page—

THOM, C. C., and HOLZ, H. F.
1914. Dry farming in Washington. (Washington Agricultural Experiment Station, Bul. 69.) 159

TIMIRIAZEFF, C. A.
1912. Life of the plant. (Lond., p. 159.) 188

WIDTSOE, J. A., and MERRILL, L. A.
1902. Arid farming, or farming without irrigation. (Utah Agricultural Experiment Station, Bul. 75.) 37, 159

WIDTSOE, J. A.
1909. Irrigation investigations. Factors influencing evaporation and transpiration. (Utah Agricultural Experiment Station, Bul. 116, 64 pp.) 31, 34, 37, 143, 159
1912. The production of dry matter with different quantities of irrigation water. (Utah Agricultural Experiment Station, Bul. 116, 164 pp.) 23

WILFARTH, H., and WIMMER, G.
1902. Die Wirkung des Kaliums auf das Pflanzenleben nach Vegetationsversuchen mit Kartoffeln, Tabak, Buchweizen, Senf, Zichorien, und Hafer. (Arbeiten der Deutschen Landwirtschafts-Gesellschaft, Heft 68, Berlin, 106 pp.) 37, 143, 170

WILLARD, R. E., and HUMBERT, E. P.
1913. Soil moisture. (New Mexico Agricultural Experiment Station, Bul. 86, 86 pp.) 37, 143, 159

WILMS, JOHANN.
1899. Einfluss des Wassergehalts und Nährstoffsreichtums des Bodens auf die Lebensthätigkeit und Ausbildung der Kartoffelpflanze. (Journal für Landwirtschaft, v. 47.) 37, 143

WIMMER, G.
1908. Nach welchen Gesetzen erfolgt die Kaliaufnahme der Pflanzen aus dem Bodens? (Arbeiten der Deutschen Landwirtschafts-Gesellschaft, Heft 143, Berlin, 169 pp.) 37, 143, 170

WOLLNY, E.
1877. Einfluss der Pflanzendecke und der Beschattung auf den Wassergehalt des Bodens. (Der Einfluss der Pflanzendecke und Beschattung auf die physikalischen Eigenschaften und die Fruchtbarkeit des Bodens. Berlin, pp. 105-135.) 37, 87, 159

WOODWARD, JOHN.
1699. Some thoughts and experiments concerning vegetation. (Philosophical Transactions, Royal Society, London, v. 21, no. 253, pp. 193-227.) 20

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